

**Kyoto and Beyond:  
How the banking rule affects emission, cost and price**

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## Foreword

For more than a year the Kyoto Protocol and emission permits has been at the top of my head as work has progressed with this thesis. During the same period, the world around me has been very much occupied with the same issues. This has made my work more exciting, as I realize that what I do at the University relates to the world outside. On that note, I want to thank my supervisors Odd Godal and Sigve Tjøtta for having the foresight to establish a masters group working on environmental economics. The work in our group has been rewarding and motivating. The support I have received from both counselors has been extensive and very useful.

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I also want to mention Jonas Christensen and Magnus Reitan, fellow students and great discussion partners when I needed to develop my ideas. They have also helped me with reading through the thesis. Any mistakes are however mine alone.

My employer, DnB NOR has given me time and flexibility to finish this thesis, even though I started working for them six months before this thesis was due. I really appreciate this, and their commitment in getting me to finalize my degree.

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## **Abstract**

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In this thesis I investigate numerically how three different scenarios of a Post-Kyoto agreement for the commitment period 2013-2017 affect the overall emission abatement, the cost of compliance and the price for emission permits in both the Kyoto (2008-2012) and the Post-Kyoto periods. The scenarios affect both periods through the banking rule; one of the compliance rules governing the emission trade mechanism in the Kyoto Protocol. In my results, banking reduces the overall cost of abatement and shifts abatement from the subsequent period to the present, when the Post-Kyoto emission targets are lower than in the present period. Due to over allocation of permits in the Kyoto period, so called “hot air”, it also causes a higher overall emissions, compared to a non-banking version of the same market, due to the possibility of bringing surplus permits from the Kyoto period into the next period. The numerical analysis in this thesis has been done using GAMS.

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# 1. Introduction

One of the rules governing the emission trade mechanism of the Kyoto Protocol is the so called banking, or carry-over rule. This allows the participants to save emission permits from one commitment period to the next. Looking at the two first commitment periods in the Kyoto Protocol, I will do a numerical analysis of how banking influence the abatement in each period, the total compliance cost and the emission permit price in the market.

What makes banking interesting is that it connects the commitment periods. If the international community agrees that it is important to start reducing greenhouse gas emissions sooner, rather than later, connecting the periods could help achieving this by letting stricter abatement targets in the future influence the current market.

The banking rule was agreed upon in the Marrakesh Accords from 2001 and together with the other rules for the emission trading, it now governs the emission permit market in the first Kyoto commitment period (2008-2012). How the banking rule will affect abatement across two periods, the total compliance cost and the permit prices, can only be determined once a follow-up to the Kyoto Protocol is agreed upon. This Post-Kyoto agreement will set the framework for the next commitment period (2013-17). Currently, this agreement is supposed to be finalized in Copenhagen in December 2009. Therefore, in order to be able to examine the banking rule numerically, I have had to make assumptions regarding what this agreement will look like.

According to Springer (2003) making assumptions on a possible Post-Kyoto agreement is “highly speculative”, which is why I have included three different scenarios. The first is a duplicate of the Kyoto Protocol in one more period; in the second scenario the same countries take on emission targets as in the current agreement, but the targets are stricter. Finally a third scenario is assumed where USA, China and India also commits to the scheme, and overall emission reduction targets are tightened even further. I look at the consequences of each of the scenarios with and without banking.

In theoretical works since Cronshaw and Kruse (1996) and Rubin (1996) it has been established that banking can lower the total abatement cost for participants in an emission trading scheme with abatement goals set across more than one period. Also empirical reviews of the U.S. Acid Rain Program which allowed banking, show that intertemporal trade reduces overall compliance cost and shifts abatement forward in time, i.e. abatement is done earlier (Ellerman and Montero, 2007).

My results follow these works in showing that if a second commitment period to the Kyoto Protocol is stricter than the current, banking will lead to an increased emission abatement in the current period. I also find that the total mitigation cost is considerably lower due to the possibility of smoothing abatement cost across both periods, and not only across regions of the world.

In my opinion, the results also show that the much debated problem of “hot air” can partly be solved by banking. This problem is widely documented in the literature (see for example Manne and Richels, 2004 or Springer and Varilek, 2004), and has its base in the fact that that the endowments in the Kyoto period are larger than the demand for emission permits in the same period. Without banking, this “hot air” means that both the cost of compliance and the price of emission permits in the first commitment period is nil, assuming no strategic behavior by the holders of the “hot air”. Such strategic behavior could be forming cartels or acting as a monopolist. With banking and gradually tighter emission schemes in the future, these excess permits are brought into the next periods and utilized.

If the goal is to achieve emission reduction sooner, rather than later, my results show that this can be achieved even with excess permits in the first period, given banking. Total emissions across the two periods does however rise with banking due to the same fact: The excess permits in a non-banking market are not used, while in a banking market they are used in the next period.



Due to the many assumptions I have had to make, the validity of my numerical results is limited. Especially excluding the possibility of strategic behavior in the current period seems unrealistic if the price otherwise would be zero. The general conclusion is, in my opinion, still valid: Banking shifts abatement forward (abatement is done earlier, rather than later) if new, stricter abatement goals are in place for subsequent periods and the overall mitigation savings are considerable. This thesis shows this numerically, utilizing the actual endowments of the Kyoto period, estimated cost functions for the participating regions and assumptions on a future agreement.

The thesis has the following structure: I start by giving a brief background on the Kyoto Protocol, the markets for emission permits and the rules that govern it in chapter 2. A brief review of the literature on intertemporal emission trade is also included. In chapter 3 I set up a model for emission trading with banking, followed by the numerical simulations of the market in chapter 4. The simulations are done using the General Algebraic Modeling System (GAMS). In chapter 5, I discuss the results in light of the limitations there are to my model, data and results. Finally, in chapter 6, I make some concluding remarks about my results. The appendix is a transcript of the GAMS program I have used, with the results.

## 2. Background

*“Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level (...) Most of the increase in global temperatures since the mid-20<sup>th</sup> century is very likely due to the observed increase in anthropogenic [greenhouse gas] concentrations.” (Climate Change 2007, Intergovernmental Panel on Climate Change, 2007)*

2007 was the year when the IPCC concluded that it is very likely that human activity since 1750 has been a major contributor to the global warming (anthropogenic emissions). They also concluded that this might have severe economic and human consequences for the world, and finally that actions trying to mitigate these effects need to be taken sooner rather than later in order to be able to stabilize, and eventually turn this trend.

Global warming has however been an issue in international politics since the 1980s. In 1992, at the United Nations Conference on Environment and Development in Rio de Janeiro, more commonly known as the “Earth Summit”, the UN Framework Convention on Climatic Change (UNFCCC) was signed. This is a treaty aimed at stabilizing the greenhouse gas concentration in the atmosphere in order to prevent dangerous climatic changes. Today 192 countries have ratified the UNFCCC, including the USA.

The governing body of UNFCCC is the Conference of Parties (COP) which has been hosted almost every year since. In 1997, at the COP 3 in Kyoto, Japan, the most famous and important update (Protocol) to the UNFCCC was agreed upon: The Kyoto Protocol. This was the first time the developed countries, known as the Annex I countries of the UNFCCC, agreed to reduce emissions in a legally binding document. In the Kyoto Protocol, the developed countries are listed in Annex B, thus Annex I of the UNFCCC and Annex B countries of the Protocol are synonymous. I will refer to them as Annex I countries in this thesis.

## 2.1 The Kyoto Protocol

In the Kyoto Protocol, the Annex I countries agreed to reduce greenhouse gas emissions during the first commitment period from 2008-12 by 5% compared to the countries' 1990-emission. Each of the participating countries are given emission endowments allowing them to emit their agreed amount for the five-year period.

The major difference between the UNFCCC and the Protocol was that while the former encouraged the developed countries to stabilize greenhouse gas emission, the latter commits them to do so<sup>1</sup>. In order to enter into force, the Protocol states that 55 countries and countries that are responsible for at least 55% of the 1990 Annex I emissions has to ratify it. After the Protocol was finalized in 1997, it entered into force in 2005, following the ratification by Russia. Today 180 countries have ratified the Protocol (including non-Annex I countries) representing about 63,7% of the 1990 Annex I emissions. The major Annex I exception is USA who has not ratified the Kyoto Protocol.

In order to reach their overall 5% reduction goal, the Annex I countries have been given three flexible mechanisms, also known as the Kyoto Mechanisms: Joint Implementation (JI), the Clean Development Mechanism (CDM) and Emission Trading. The banking rule that I will examine in the following chapters is one of the rules governing the Emission Trading mechanism. Here is a short survey of the three mechanisms (Malvik and Westskog, 2001):

- *Joint Implementation (JI)*

This is a credit-trading program which allows Annex I countries to undertake emission reduction projects in other Annex I countries where the resulting emission reduction partly or totally helps the financing country reach their own Kyoto target. Both parties must approve of the arrangement.

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<sup>1</sup> Facts regarding the Protocol are taken from: [http://unfccc.int/kyoto\\_protocol/items/2830.php](http://unfccc.int/kyoto_protocol/items/2830.php)

- *The Clean Development Mechanism (CDM)*

The CDM mechanism is a modified version of the JI mechanism. It is designed to help developing countries (non-Annex I countries) achieve sustainable development and to help Annex I countries meet their reduction targets. An Annex I country can assist the developing country through technological and financial inflows to develop more energy efficient industry and consequently reduced emission of greenhouse gases. The Annex I country can use the emission reduction in these projects to achieve their own abatement goals.

- *Emission Trading*

This is the mechanism that has received most attention, and it gives the Annex I countries the flexibility to smooth their abatement cost both spatially and temporally through trading the emission endowments. The committed countries can sell and buy the endowed emission permits to and from other Annex I countries. The theory of emission permit trade is presented in detail in chapter 3.

In addition to these mechanisms, the Marrakesh Accords (from COP 7 in Marrakesh, Marroco 2001), require that: “domestic actions (as opposed to use of the mechanisms) constitute a significant element of the efforts made by each Annex I Party to meet its target under the Kyoto Protocol”<sup>2</sup>. No quantified target is set as to how much of the abatement need to be done domestically. A further explanation of the rules of the Marrakesh Accords follows in the next section.

During the 10 years since the Protocol was signed until the first commitment period started on January 1, 2008, some major issues have occurred. Most noticeable is the fact that after the change of administration in the USA in 2001, they decided not to ratify the agreement. This means that the largest demander for permits is out of the market.

A consequence of the non-participation of the US is that the amount of permits in the market will exceed the Business-As-Usual demand for permits (BAU demand:

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<sup>2</sup> [http://unfccc.int/kyoto\\_protocol/mechanisms/items/1673.php](http://unfccc.int/kyoto_protocol/mechanisms/items/1673.php)

Unconstrained demand for emission permits) in the first commitment period. This is mainly caused by the fact that the countries of Eastern Europe and the former Soviet Union already have Business-As-Usual emissions below their 1990-level due to their inefficient industries in 1990 (Manne and Richels, 2004). In my numerical simulations this so called “hot air” will affect the results.

In December 2007, at COP 13 at Bali, Indonesia, a course was set out to make a follow-up agreement to the Kyoto Protocol. This agreement will run in the next commitment period from 2013-2017, and is planned to be finalized in 2009, at COP 15 in Copenhagen, Denmark.

## 2.2 The Rules of the Market and Borrowing

The Marrakesh Accords is a detailed description of the rules for the emission trading mechanism. In the following I describe in brief the four major rules (Godal and Klaassen, 2006). The periods in these rules refer to the 5-year long commitment periods.

- *The commitment period reserve rule* states that the countries must keep a reserve of permits equal to at least 90% of the endowments or 100% of the most recently reviewed emission inventory. This rule has been created to make sure none of the Annex I countries “over-sell” permits and then are not able to reach their emission target.
- *The banking, or carry-over rule*, allows the countries to be in over-compliance in one period and save the surplus permits to the next period.
- *The restoration rate rule* states that for each permit a country is short in the first period, 1.3 permits are to be subtracted from the next period’s endowment.
- *The suspension rule* states that countries borrowing permits in one period will be suspended from the right to sell permits in the next period, until they return to compliance.

The restoration rate and suspension rules govern what would be borrowing in the Kyoto framework. I have not included this in my analysis, and a few comments should be made as to the reasons for this:

The restoration rate rule says that if a country borrows, i.e. is non-compliant in the first commitment period (emits more pollution than the permits allow), a 30% “interest rate” is paid on every permit borrowed from the next period. Saving, or banking, permits can be done at a one-to-one basis. There is thus a strong disincentive for borrowing. In addition to this, the suspension rule stipulates that if there has been borrowing, the

country is not allowed to sell permits in the subsequent period until it is back in compliance.

Intuitively, it is reasonable to believe that borrowing will be relevant in the situation where the price of permits is higher in the first than in the second period. Assuming that the next agreement will be stricter than the Kyoto Protocol in respect to abatement goals, it would not seem probable that the price would fall. Also, the fact that the endowments in the Kyoto period are larger than the demand for permits in the same period, supports this intuition.

According to Westskog (2000) borrowing would most likely reduce total abatement cost, but due to the strong indications that borrowing will not be an issue in the current Kyoto period from the next, I have chosen to exclude it from my analysis.

The reason why borrowing has been left out of the Kyoto Protocol as a viable option is, according to Malvik and Westskog (2001), due to the fear of increased opportunities for free-riding. With the lack of a supranational authority to govern, a domestic change of government could change their policy regarding cooperation with the international community. If borrowing was widely used, it could be tempting for a government to withdraw from the agreement after the first period.

## 2.3 The Literature

In this section I outline the theoretical background for the model I present in the next chapter.

Since Montgomery (1972) the idea of using market-based emission trading has been present both in theory and in policy processes when developing emission trading schemes. His paper is partly based on the work done by Dales (1968), who is generally credited for introducing the notion that marketable emission permits may be used for pollution control (Perman et al., 2003, p. 239). Montgomery proves that an efficient market equilibrium exists for the emission market, given convex cost functions, and has been much cited for this results since. One conclusion is that for any given emission target, a market for tradable emission permits can achieve this at the lowest overall abatement cost.

Cronshaw and Kruse (1996) extends Montgomery's static results to include dynamics in discrete time, and were among the first to scientifically examine the banking of permits across periods. At this time banking had already been implemented in the SO<sub>2</sub> allowance trading scheme under the 1990 Clean Air Act amendments in the USA. Ellerman and Montero (2007) provides an empirical evaluation of banking in this market. Rubin (1996) extends Cronshaw and Kruse's model in continuous time, and includes borrowing. The conclusion from both Cronshaw and Kruse and Rubin is that with banking, a target level of emission over more than one time period will be reached at the lowest present value of cost. Essentially, it is the same logic as in Montgomery, except that the trade is not only allowed across sources, but also across periods.

Finally, Kling and Rubin (1997) looks at the efficiency properties of a similar banking model, concluding that the private solution in a market where both banking and borrowing is allowed, does not always correspond to the social optimum. The reason is that with falling prices of emission permits in present-value, participants will want to borrow permits, resulting in excessive pollution damage in the first period compared to



the social optimum. They suggest a solution to this by outlining a modified banking system with disincentives to borrowing. The restoration rule of the Marrakesh Accords is an application of this result.

Interesting literature regarding banking has been left out here since it examines aspects of the market not included in my analysis. Parts of this literature is commented on in chapter 5 where I discuss my results.

### 3. The Model

This is a presentation of a model representing the emission trading market of the Kyoto Protocol. First, the model is presented in one period. Later, the participants can save their permits to a subsequent period. The latter case is the full banking model in two periods that I program in GAMS and use for my numerical analysis in the proceeding chapter. I only analyze the numerical effects of the banking rule. The restoration rate rule, commitment period reserve rule and the suspension rule are thus not included in the model.

I draw on several sources in this presentation, mainly Montgomery (1972), Hanley et al. (1997) and Perman et al. (2003) for the one-period model and Cronshaw and Kruse (1996) and Godal and Klaassen (2003, 2006) for the intertemporal model.

The emission trading mechanism outlined in the Kyoto Protocol is based on the assumption that a market of rights to pollute will make abatement happen where, and when, it is of least cost. With a price related to pollution, participants<sup>3</sup> are likely to include this as an argument in their total cost functions when minimizing costs, assuming they are cost minimizers. Through this process they decide what their emission level should be and subsequently whether to buy permits, or to abate emission. This is why a model like this is relevant when doing a numerical analysis of the Kyoto Protocol and its possible follow-up.

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<sup>3</sup> “Participant” is in the following referring to the Annex I parties of the UNFCCC.

### 3.1 Assumptions

- *A “cap-and-trade” model.*

In the Kyoto framework a total cap is decided by international negotiations for the target of overall emission. The total amount of permits distributed equals this target level of emission, or the cap. Through the same international negotiations, it is decided how to distribute the permits between the polluting participants, i.e. how the individual emission targets should be. The total amount of permits in the market is always constant.

- *Emission permits can be freely traded between the participants.*

Within each commitment period, these permits can be traded freely at a one-for-one rate between the participants. Selling one permit, means abating one more unit of emission. There are no transaction costs considered.

- *n participants with different costs of emission abatement.*

In the Kyoto framework each participant is a national government.

- *Each participant has a set of permits allocated free of charge based on historical emissions (“Grandfathering”).*

Another way of distributing the permits among the participants could be by auction, or by just selling them at a predetermined price.

- *The participants can only emit pollution equal to the number of emission permits they have been granted or acquired through trade.*

I will assume that this restriction is respected by the participants.

- *The participants are cost minimizers. This is their only motive when deciding how many permits to hold.*

- *The markets are perfectly competitive and there is no strategic behavior.*

All the participants are price-takers with no individual market power. Neither will they form cartels with other participants to gain market power.

- *Emissions are uniformly mixing pollutants.*

The geographical source of the pollution is irrelevant. Uniformly mixing pollutants quickly disperse and affect the environment globally. Greenhouse gases is one example of a uniformly mixing pollutant. The model I present works well for these kinds of pollutants. If the emission do not have these properties, the model will not apply as two participants emissions may have different impacts on the environment at different places.

- *No participant will choose a level of pollution emissions higher than the one observed in the absence of emission regulations.*

This means that Business-As-Usual estimates are always the maximum the participants will emit.

- *There are no negative emissions.*

Measures such as planting trees in the rainforest or the capture of greenhouse gases in the seabed, and thus reducing the greenhouse gases in the atmosphere, are not included in this model.

- *Only positive banking is allowed.*

When the model is expanded to two periods, the participants will be allowed to save permits for the next commitment period, but not borrow (negative banking) from it.

## 3.2 Emission Permit Trade in One Period

In the following the subscript  $i$  represents the participants of this model. In the Kyoto framework, this is the national governments of the Annex I parties.  $x_i$  denotes the amount of permits held by each participant. This equals the amount of emissions by each participant within this model.

$C_i(x_i)$  is the cost function which is at the base of the following presentation. From Montgomery (1972) this function relates different levels of restricted emission to the cost of production for a cost minimizing participant.

In the case where there is no restriction on emission, the participant will have no cost related to the emission  $C_i(x_i) = 0$ . We also know that at  $x_i = 0$ , which is the case when no emissions are allowed, the participant will have the maximum possible costs related to emission.

I assume that the cost function is twice differentiable and convex in  $x_i$ , that is,  $C_i'(x_i) < 0$  and  $C_i''(x_i) > 0$  which means that the cost related to emission for the participant decreases as  $x_i$  increases. Intuitively, more emission means lower cost related to maintaining this level of emission, or in reverse: As emission restrictions become more severe, the cost of abatement increases as the least expensive measures to cut emissions are done first.

### 3.2.1 Single participant optimization with exogenous prices

With a function relating the emission level with cost, we can include the market for emission permits. The total cost function that the price-taking participants will minimize include the potential expenses of trading permits.  $e_i$  represents the individual amount of permit endowments. The difference  $(x_i - e_i)$  is the amount of permits bought (positive difference) or sold (negative difference) at the exogenous market price  $p$ .

The total cost that the participants will minimize is:

$$TC_i(x_i) = C_i(x_i) + p(x_i - e_i) \quad (3.1)$$

The first order condition for the cost minimization is:

$$\frac{\partial TC_i(x_i)}{\partial x_i} = C_i'(x_i) + p = 0 \quad (3.2)$$

The second order condition for the minimization is fulfilled since the cost function is assumed convex. Remembering that the cost function relates a cost to a certain level of emission, we can now observe that the marginal abatement cost (MAC), the negative of the marginal cost of emitting one more unit of the pollutant, is equal to the price of permits in optimum. Rearranging (3.2) we get:  $p = -C_i'(x_i) = MAC_i$ .

A price taking, cost minimizing participant will therefore, in a situation where emission constraints are imposed, set emissions at a level where the marginal cost of abatement is equal to the price of emission permits.

Intuitively, with a given price of permits, the participant will adjust emissions to the level where abating one additional unit of emission has the same cost as the price of the emission permits. With different cost functions, this level may vary between the participants. This guarantees that the emission abatement is done where it is of least cost. Let us consider the alternatives to see that (3.2) must give a minimum (remember that we are considering a single, price-taking firm):

$p < -C_i'(x_i)$ : The cost of abating another unit of pollution is above the price of pollution permits. Assuming that the participant has been given a restriction which is below their unrestricted demand for emissions, they would have an incentive to buy permits instead

of reducing emissions. This will happen until the participant reaches the level of emission where an additional permit will cost the same as reducing an emission unit.

$p > -C_i'(x_i)$ : For this participant it is of less cost to abate emission than to buy permits. This participant would rather abate emission than buy permits. If they have been allocated permits which allows them to emit pollutants at a level where the price of the permits is higher than their marginal abatement cost, they can make a profit from selling some permits and reducing emissions. This will happen until they reach a level of emission where the cost of reducing another unit equals the price of the permits. And we are back to the total cost minimum situation described above.

If we had assigned functional values to the cost function, we could have solved the first order condition in (3.2) with respect to  $x_i$  to find an expression for the demand of emission permits from participant  $i$ , with respect to the price,  $x_i(p)$ . In the next subsection this will be used when adding up all the individual demands in the market.

### 3.2.2 The market clearing

If we add these individual demands for all  $n$  participants, and set this equal to the total amount of permits in the market:

$$\sum_{i=1}^n x_i(p) = \sum_{i=1}^n e_i \quad (3.3)$$

and solve for  $p$ , we find the market price of emission permits. (3.3) thus represents the market clearing condition for a simple emission permit system. It is quite intuitive: The total amount of individual emissions in the market can never be higher than the target of total emissions defined by the “cap” or total amount of endowments. This was also one of my assumptions.

### 3.2.3 Computing the equilibrium

Finding the market price can also be done using Lagrange. The market problem is to minimize the total costs (TC) of all the participants in the market:

$$TC^{Market} = \sum_{i=1}^n C_i(x_i)$$

$$\min TC^{Market} \text{ subject to } \sum_{i=1}^n x_i = \sum_{i=1}^n e_i$$

Assigning a multiplier  $\lambda$  to the constraint, the Lagrangian for this problem becomes:

$$\ell(x_i, \lambda) = \sum_{i=1}^n C_i(x_i) + \lambda \left( \sum_{i=1}^n x_i - \sum_{i=1}^n e_i \right) \quad (3.4)$$

which gives us the first order condition:

$$\frac{\partial \ell}{\partial x_i} = C_i'(x_i) + \lambda = 0 \quad (3.5)$$

and our market clearing restriction:

$$\sum_{i=1}^n x_i = \sum_{i=1}^n e_i$$

We see that (3.5) is equal to (3.2), but instead of the price, we have a constant multiplier expressing a shadow price which can be read as the market price of permits. It also shows that all marginal abatement costs will be set equal to the price in the market equilibrium for the least cost solution. This result is the same as we attained for the single participant and essential for any emission trading models.



### 3.3 Emission Permit Trade in Two Periods

Now I extend the model to a second period<sup>4</sup>. I also allow the polluting participants to save their pollution permits from period 1 to period 2. The price of the permits may vary between the periods, but I assume the market ends after period 2, so a permit has no value after the end of this period. The sum of the permit endowments in the second period might be larger (a looser agreement), or smaller (a stricter agreement) than in the previous period. Also individual endowments might change from one period to the next. The main reasons for such a variation will be that more participants take on emission targets, or that the governments of the already committed nations change their targets for emission abatement.

The reasons for allowing banking are roughly the same as for allowing permit trade at all. In the previous section we saw how permit trade enabled the market to allocate abatements to the participants with least marginal abatement cost within one period. Opening up the trade, not only between participants within one period, but also between periods, gives an even larger opportunity to smooth abatement costs and allowing the pollution targets to be reached at a least aggregate cost over all periods (Rubin, 1996).

It is important to distinguish between intertemporal trade within the commitment periods and between subsequent commitment periods. In the former, both saving and borrowing is allowed, but in the latter case only saving is.

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<sup>4</sup> The second commitment period in the Kyoto framework runs in 2013-2017.

### 3.3.1 Single participant optimization with exogenous price

A comment on notation: The superscript in the following denotes time,  $t = 1, 2$ . Since the model only include two periods I will denote periods by the number of the period rather than the general  $t$ . When expressions are of such a nature that it can be valid for both periods, I will denote this by  $t$ .

$s_t$  represents savings or banking. This is the amount of permits that are brought from the first to the second period. This can never be a negative number (which would be borrowing).  $\rho$  denotes the discount factor.

Formally, the total cost function for the two period emission trading model with banking for a single participant is:

$$TC_i(x_i^1, x_i^2, s_i) = C_i^1(x_i^1) + p^1(x_i^1 - e_i^1 + s_i) + \rho [C_i^2(x_i^2) + p^2(x_i^2 - e_i^2 - s_i)] \quad (3.6)$$

The total cost function in (3.6) is analogue to (3.1), but this time I have included a second period and saving.

To find the discounted total I have included  $\rho = \left(\frac{1}{1+r}\right)^{years}$  as the discount factor, where  $r$  = real interest rate and it is raised by the number of years of the commitment period. The trading part of each period is the same as in (3.1), but savings are added in the first period, and subtracted in the second.

Intuitively, this is because  $x_i^t$ , being the actual holding of emission permits in each period, must be covered by either the endowments  $e_i^t$ , or the permits participants buy (or have banked, for the second period).

If  $e_i^1 < x_i^1$  then  $(x_i^1 - e_i^1 + s_i) > 0$ , which means that permits have to be bought to cover the difference. If participants choose to save permits in addition to this, it must also be added. The sum of permits bought to cover their demand and the saving, has to be acquired at the price in the first period.

If  $e_i^1 > x_i^1$  then  $(x_i^1 - e_i^1 + s_i)$  can be zero, if the excess permits are saved; negative, if the excess permits are sold in the first period; and finally positive, if they choose to save more than their excess permits. If the participant is a net seller in the first period, the sum of the trade is negative, and subtracted from the total cost. If they are net buyers, the positive sum is added to the cost.

The logic works in reverse in the second period. If the amount of endowed permits is less than the demand for permits, the difference must be covered by buying permits, or by having permits banked from the first period. This is why the savings has to be subtracted in this period.

As we see from (3.6), the cost function can vary from the first period to the second. This can happen in two ways: By general exogenous technological development in the economy, which is denoted by the time-superscript to  $C_i$ ; or through the emission reductions they undertook in the first period, which is why the second phase emission cost function not only depend on the second period demand for emission permits,  $x_i^2$ , but also  $x_i^1$ . This could be the installation of new equipment or R & D costs undertaken by the participant in the first period, which also reduces the cost of emission in period 2.

In the following I will let the general technological development be the only way the second phase emission cost functions can change; thus  $C_i^2$  only depends on  $x_i^2$ .

The minimization problem of the individual participant is:

$$\min TC_i(x_i^1, x_i^2, s_i) \text{ subject to } \begin{cases} s_i \geq 0 \\ s_i \leq \sum_{i=1}^n e_i^1 \end{cases} \quad (3.7)$$

The first restriction simply states that saving has to be non-negative, i.e. borrowing is forbidden, which is consistent with what I have assumed from the beginning. The second one is included since there cannot be saved more permits than exists in the market. In an extreme case with these restrictions, one participant could save all the permits in the market, and then nobody else would be able to save. The restrictions would still be valid however, since if a participant do not save, they still fulfill the restriction.

When we associate constant Lagrange multipliers with the constraints, we can define the Lagrangian function:

$$\ell(x_i^1, x_i^2, s_i, \lambda_1, \lambda_2) = C_i^1(x_i^1) + p^1(x_i^1 - e_i^1 + s_i) + \rho [C_i^2(x_i^2) + p^2(x_i^2 - e_i^2 - s_i)] - \lambda_1 s_i + \lambda_2 (s_i - \sum_{i=1}^n e_{i,t}) \quad (3.8)$$

I assume interior solutions for  $x_i^1$  and  $x_i^2$ . The Kuhn-Tucker conditions are:

$$\frac{\partial \ell(\cdot)}{\partial x_i^1} = C_i^{1'}(x_i^1) + p^1 = 0 \quad (3.9)$$

$$\frac{\partial \ell(\cdot)}{\partial x_i^2} = \rho C_i^{2'}(x_i^2) + \rho p^2 = 0 \quad (3.10)$$

$$\frac{\partial \ell(\cdot)}{\partial s_i} = p^1 - \rho p^2 - \lambda_1 + \lambda_2 = 0 \quad (3.11)$$

$$s_i \geq 0 \tag{3.12}$$

$$\lambda_1 \geq 0 ; \lambda_1 s_i = 0 \tag{3.13}$$

$$s_i \leq \sum_{i=1}^n e_i^1 \tag{3.14}$$

$$\lambda_2 \geq 0 ; \lambda_2 (s_i - \sum_{i=1}^n e_i^2) = 0 \tag{3.15}$$

Rearranging (3.9) and (3.10), we find a familiar result:  $p^1 = -C_i^1'(x_i^1)$  and  $p^2 = -C_i^2'(x_i^2)$ , namely that optimal emission levels at minimum total cost are at the points where the permit price equals the marginal abatement cost in each period.

Remembering that we are in a perfect market where no participants exert market power, we can now discuss the possible relationships between the permit price in period 1 and period 2. For the moment these prices are assumed exogenous.

If  $p^1 > \rho p^2$  we see from (3.11) that  $\lambda_1$  has to be positive. From (3.13) this implies that  $s_i = 0$ , i.e. no banking. This means that if the price of permits in the first period is higher than the discounted permit price in the second period, the participant will not save permits. Knowing this, we also see from (3.15) that  $\lambda_2 = 0$ . This is how the model restricts negative saving (borrowing).

If  $p^1 < \rho p^2$  we see from (3.11) that  $\lambda_2$  has to be positive, which again means that in (3.15),  $s_i = \sum_{i=1}^n e_i^1$ . This is a positive saving, but not only that, with the discounted price of permits higher in the next period than in the current period (remember that so far prices are assumed exogenously given), the participants will have incentives to save all they can. This is only restricted by the upper limit set by the total amount of permits in the economy in period 1. Thus in the case of the price differential going this way, a single

participant would try to acquire and save all the permits available in the market. Intuitively it is hard to believe that this can be an equilibrium in the market, since it means all participants will want to save all permits. I will return to this when the market solution is discussed.

If  $p^1 = \rho p^2$ , expression (3.11) can only be satisfied by having  $\lambda_1 = \lambda_2 = 0$ , since both of these multipliers cannot be positive at the same time.

If they were both positive, and equal, the equality of the prices could still exist according to (3.11), but having  $\lambda_1$  positive in (3.13) signifies having  $s_i = 0$ , which inserted in (3.15) requires  $\lambda_2 = 0$ . Thus having both multipliers positive is impossible in this model.

With  $p^1 = \rho p^2$  there can be different levels of saving since having  $\lambda_1 = \lambda_2 = 0$  means that  $s_i$  can vary in both (3.13) and (3.15). Since  $s_i$  is added in the first period and subtracted in the second period in (3.6), this implies that saving has no net effect on total cost in this situation. The reason is that it is multiplied by the same price in both periods.

An important note needs to be made here regarding the individual amounts of saving. We see that if the discounted price of the second period is equal, or greater than the price of the first period, it opens up for individual savings. If the discounted second period price is higher than the first period price, all participants will want to save all permits; a situation which I will return to in the next subsection. But if  $p^1 = \rho p^2$ , a unique  $s_i$  for each individual is not given by this model.

This is explained by (3.11): When prices are equal in present value, the total cost is a constant and linear function of  $s_i$ . Thus no unique amount of  $s_i$  can be determined. Many solutions are possible, and they all constitute a total cost minimum, since total cost in this situation is unaffected by savings.

This fact will also have implications for the calculation of the cost. From (3.6) we see that knowing  $x_i^t$  we will be able to find  $C_i^t(x_i^t)$  for each period. When it comes to the trade part of the total cost function, we will not be able to say anything about the individual cost of this in each period due to the fact that individual saving is not unique. But across the two periods we do find the cost of trading with equal present value prices, since the savings cancel itself over the two periods. When I present my numerical results in the next chapter, this is reflected in the reporting of the costs.

To conclude, we have found that in the case of a single price-taking participant the relationship between the permit prices in the two periods will decide if the participant saves permits or not. If the discounted price is higher in the last period than the price in the first, the participant will try to save all permits in the market of the first period. If the price is higher in the first period, they will not want to save. And finally, if the discounted price of period 2 is equal to the price in period 1, there can be saving. And it will not necessarily be of all the permits in the market. The amount is however impossible to uniquely tell for each individual in this model.

### 3.3.2 The market clearing

The market clearing conditions for the two-period banking model are for all  $i$ :

$$\left\{ \begin{array}{l} \sum_{i=1}^n x_i^1 - \sum_{i=1}^n e_i^1 + \sum_{i=1}^n s_i = 0 \\ \sum_{i=1}^n x_i^2 - \sum_{i=1}^n e_i^2 - \sum_{i=1}^n s_i = 0 \\ s_i \geq 0 \end{array} \right. \quad (3.16)$$

The market constraints in (3.16) represent the logic behind the banking mechanism. In the first one, the sum of emission permits being held across all participants in the first period cannot be higher than the sum of all endowments in that period. If it was, it would mean that they would have to borrow, which is forbidden in this model. If the sum of emission permits being held across all participants is less than the total endowment, the participants will transfer the left over endowments into the following period. This is the sum of savings across all participants.

The second constraint is made in the same way, but here, the sum of emission permits being held across all participants can be higher than the total second period endowments. The excess demand for permits in this period must however be covered by the sum of saved endowments from the first period.

As already discussed, the individual savings cannot be uniquely determined from the model. The sum across all participants is however known. The reason is simple: From the solution for the individual participants, optimal  $x_i^t$  will be given by the model for each participant and the individual endowments,  $e_i^t$ , are given exogenously. As long as the total endowments across the participants in both periods is lower than the unrestricted demand for permits (Business-As-Usual) in both periods, the sum of saving will always be the residual between what is held in the first period and that period's endowments. This is why the restrictions hold, even though the individual savings are unknown.



The third constraint is the same one as in the single-participant case, it simply states that saving cannot be negative.

The last constraint from the single-participant minimization is absent. The reason for this is that the restriction  $s_i \leq \sum_{i=1}^n e_i^1$  is redundant in a market optimization. Intuitively we recall that this restriction limited the individual saving to the total amount of endowments across all participants in one period. In a market, with several participants, it is impossible that one participant will be able to get all permits available.

Formally, we see that if we set  $s_i = \sum_{i=1}^n e_i^1$  then  $\sum_{i=1}^n s_i = \sum_{i=1}^n \sum_{i=1}^n e_i^1 = n \sum_{i=1}^n e_i^1$  which inserted in

the first market constraint is a contradiction:

$$\sum_{i=1}^n x_i^1 - \sum_{i=1}^n e_i^1 + n \sum_{i=1}^n e_i^1 \Rightarrow \sum_{i=1}^n x_i^1 + (n-1) \sum_{i=1}^n e_i^1 \neq 0$$

Thus we omit this restriction in the market case.

### 3.3.3 Computing the equilibrium

In the market version of the two-period banking EPS, the total cost function becomes:

$$TC^{Market} = \sum_{i=1}^n C_i^1(x_i^1) + \rho \sum_{i=1}^n C_i^2(x_i^2)$$

and the minimization problem can be expressed:

$$\min TC^{Market} \text{ subject to } \left\{ \begin{array}{l} \sum_{i=1}^n x_i^1 - \sum_{i=1}^n e_i^1 + \sum_{i=1}^n s_i = 0 \\ \sum_{i=1}^n x_i^2 - \sum_{i=1}^n e_i^2 - \sum_{i=1}^n s_i = 0 \\ s_i \geq 0 \end{array} \right. \quad (3.17)$$

I choose to solve the optimization problem once again setting up a Lagrange expression. I let  $\mu$  and  $\lambda$  be the multipliers on the equality and the inequality constraints respectively.

$$\ell(x_i^1, x_i^2, s_i, \mu_1, \mu_2, \lambda_1) = \sum_{i=1}^n C_i^1(x_i^1) + \rho \sum_{i=1}^n C_i^2(x_i^2) + \mu_1 \left( \sum_{i=1}^n x_i^1 - \sum_{i=1}^n e_i^1 + \sum_{i=1}^n s_i \right) + \mu_2 \left( \sum_{i=1}^n x_i^2 - \sum_{i=1}^n e_i^2 - \sum_{i=1}^n s_i \right) - \lambda_1 s_i \quad (3.18)$$

Solving, we find the following first order conditions:

$$\frac{\partial \ell(\cdot)}{\partial x_i^1} = C_i^1'(x_i^1) + \mu_1 = 0 \quad (3.19)$$

$$\frac{\partial \ell(\cdot)}{\partial x_i^2} = \rho C_i^{2\prime}(x_i^2) + \mu_2 = 0 \quad (3.20)$$

$$\frac{\partial \ell}{\partial s_i} = \mu_1 - \mu_2 - \lambda_i = 0 \quad (3.21)$$

$$\begin{aligned} \lambda_i &\geq 0; \\ \lambda_i s_i &= 0 \end{aligned} \quad (3.22)$$

$$s_i \geq 0 \quad (3.23)$$

The first order conditions for the market (3.19)-(3.21) are the same as the individual participant's first order conditions (3.9)-(3.11). As in the one period model, we see that the constant multipliers are proxies for the price, or shadow prices:  $\mu_1$  representing the price of permits in the first period, and  $\mu_2$  representing the discounted price of permits in period 2.

If we have banking, i.e. a positive saving of permits from period 1 to period 2,  $\lambda_i = 0$  due to (3.22). This means that (3.21) can be expressed as  $\mu_1 = \mu_2$ .

Remembering that these multipliers are the shadow prices for pollution permits, we can state that in a perfect competitive market for pollution permits, with two periods and with banking, the price in equilibrium of these permits can rise no faster than the rate of interest, from (3.19)-(3.21):  $\mu_1 = \mu_2 \Rightarrow -C_i^1 \prime(x_i^1) = -\rho C_i^{2\prime}(x_i^2)$ . Which is the same result we found in the individual solution when saving occurred. This result is analogue to what Cronshaw and Kruse (1996) concludes; participants will have incentives to save if the price rises over time with the rate of interest. In the one-period model, the participants smooth costs by equaling their marginal abatement costs across sources. This also applies for intertemporal trade; marginal abatement costs are equaled across periods.

It is quite intuitive to see why this must hold. If the price of permits rose at a rate above the interest rate, there would be an infinite demand for permits in period 1 since they could be sold in period 2 at a risk free profit. As we have seen, this would lead all participants to demand all the permits in the market, which in a market would lead the price of permits in period 1 to rise, until the above result is reached.

Formally, if we try to set  $\mu_1 < \mu_2$ , then  $\lambda_i$  would have to be negative. From (3.22) we see that this is impossible. So with endogenous prices, the discussion we had for the single participant wanting to save all the permits in the market is irrelevant. Recalling the discussion on the market constraints, this result was expected.

The reverse situation,  $\mu_1 > \mu_2$  would only be possible with a positive  $\lambda_i$ , which from (3.22) means no saving. Borrowing is restricted from (3.23).

This concludes the presentation of the model.

## 4. Numerical Simulations

In the next section I describe the data I will use in my simulations. Then I make three different scenarios for the possible follow-up agreement of the Kyoto Protocol. The motivation for making three alternatives is that I want to see how different degrees of strictness and participation affects the current commitment period and total cost due to banking. The final sections present the results from running the model from chapter three with the data and my scenarios for a Post-Kyoto agreement in GAMS.

### 4.1 The Data and Parameters of the Model

**Table 4.1: The Kyoto Protocol 2008-12 (MtC/yr)<sup>a</sup>**

	<i>1990-emissions</i>	<i>Commitment</i>	<i>Endowments</i>
USA <sup>b</sup>	1345	7,00 %	1251
OECD	934	7,90 %	860
Japan	274	6,00 %	258
CANZ	217	0,70 %	215
EEFSU	1337	1,70 %	1314
<b>Total</b>	<b>4107</b>	<b>5,10 %</b>	<b>3898</b>

<sup>a</sup> This table is taken from Godal and Klaassen (2006)

<sup>b</sup> USA never ratified the initial Kyoto Protocol and is thus not actively pursuing their 7% emission reduction goal set forth in Kyoto.

All my endowments are, like the Kyoto Protocol reproduced in table 4.1, calculated from the base year 1990. The data I use is the world's energy-related Carbon emissions that year. The parameterization in the following is derived from the MERGE model (Model for Evaluating the Regional and Global Effects of GHG Reduction policies)<sup>5</sup> as they were presented in Godal and Klaassen (2003, 2006). In the MERGE model all countries are aggregated into relevant regions. Some countries are, due to their relative sizes, left as separate regions by themselves. The regions from table 4.1 with the rest of the world are shown in table 4.2. They are: OECD (OECD Europe), EEFSU (Eastern Europe and Former Soviet Union), CANZ (Canada, Australia and New Zealand), MOPEC (Middle

<sup>5</sup> For more information, see: <http://www.stanford.edu/group/MERGE/>

East and OPEC), ROW (Rest of the world), China, USA, Japan and India. These regions are preserved and used throughout this thesis.

**Table 4.2: Regions of The World in MERGE**

<b>oecde</b>	United Kingdom	Hungary	<b>Mopec</b>
Austria	Iceland	Latvia	Middle east and OPEC
Belgium	Liechtenstein	Lithuania	
Denmark	Monaco	Poland	<b>Row</b>
Finland	Norway	Romania	Rest of the world
France	Switzerland	Russian Federation	
Germany		Slovakia	<b>China</b>
Greece	<b>Japan</b>	Slovenia	
Ireland		Ukraine	<b>India</b>
Italy	<b>Usa</b>		
Luxembourg		<b>Canz</b>	
Netherlands	<b>Efsu</b>	Australia	
Portugal	Bulgaria	Canada	
Spain	Czech Republic	New Zealand	
Sweden	Estonia		

#### 4.1.1 The cost function: functional form and parameters

The abatement cost function for the participants is taken from Godal and Klaassen (2003, 2006) and given by:

$$C_i^t(x_i^t) = \alpha_i^t - \beta_i^t x_i^t + \frac{1}{2} \delta_i^t (x_i^t)^2 \quad (4.1)$$

The parameters are positive,  $\alpha_i^t, \beta_i^t, \delta_i^t > 0$ . We remember it is impossible to have negative emissions,  $x_i \geq 0$  and as defined in chapter 3, the abatement cost function satisfies  $C_i^t'(x_i^t) < 0$  and  $C_i^t''(x_i^t) > 0$ . In this specific form this gives us a marginal cost of emission:

$$C_i^t'(x_i^t) = -\beta_i^t + \delta_i^t x_i^t \quad (4.2)$$

The second derivative also fits the assumptions:

$$C_i''(x_i') = \delta_i'$$

Due to the positive parameter, this must be positive.

A point to be aware of when working with quadratic cost functions, is that we need to limit our marginal cost function in the following way, in order to keep it within our model:

$$C_i'(x_i') = \min\{-\beta_i' + \delta_i'x_i', 0\} \quad (4.3)$$

Which simply states that the marginal effect on the cost of more emissions, can never become positive. Intuitively, a participant can only reduce cost by increasing emissions. Once they reach the level where they no longer can reduce cost by increasing emissions, they do not have incentives to rise emissions any more.

At the base of the following numerical simulations are the marginal abatement cost function parameters, provided by the International Institute of Applied System Analysis (IIASA), based on the already mentioned MERGE model. I have based my simulations on these parameters as they were reproduced in Godal and Klaassen (2003, 2006).

The parameters were made by imposing different levels of carbon tax on the model, followed by OLS regressions of the data finding linear fits for  $\beta_i'$  and  $\delta_i'$  parameters in the marginal abatement cost function. Table 4.3 shows the parameters including the  $\alpha_i'$  parameter that we remember from (4.1). The latter has been calculated by me, the former by Godal and Klaassen. I include the  $\alpha_i'$  parameter as it will be needed later on, when calculating the total cost of the different scenarios. It is derived by inserting permit

demand levels,  $x_i^t$ , equal to Business-As-Usual (BAU) in the cost function. Emission at this level imply no cost related to emissions for the participant. Formally:

$$C_i^t(x_i^t) = \alpha_i^t - \beta_i^t x_i^t + \frac{1}{2} \delta_i^t (x_i^t)^2 \quad \text{with } C_i^t(x_i^t) = 0 \quad \text{and } x_i^t = \frac{\beta_i^t}{\delta_i^t} \quad (\text{permit demand equal to}$$

$$\text{BAU) gives } \alpha_i^t = \frac{(\beta_i^t)^2}{2\delta_i^t}.$$

**Table 4.3: The Abatement Cost Function Parameters**

	2010			2015		
	$\alpha_i$ (MUSD/yr)	$\beta_i$ (USD/tC)	$\delta_i$ (USDyr/M(tC) <sup>2</sup> )	$\alpha_i$ (MUSD/yr)	$\beta_i$ (USD/tC)	$\delta_i$ (USDyr/M(tC) <sup>2</sup> )
usa	912894	1003	0,551	727456	760	0,397
oecde	977851	1883	1,813	635284	1185	1,105
japan	302304	1727	4,933	221400	1258	3,574
canz	108359	693	2,216	97524	611	1,914
eefsu	633556	1410	1,569	489092	1034	1,093
china	817388	1383	1,17	792714	1211	0,925
india	149943	971	3,144	135792	790	2,298
mopec	275655	1238	2,78	263334	1108	2,331
row	437488	816	0,761	409996	674	0,554

The notation of the cost function parameters are such that the marginal cost of emission,  $C_i^t'(x_i^t)$ , is expressed by USD/tC<sup>6</sup>. Subsequently, this also holds for the marginal abatement cost, which is:  $MAC_i^t = -C_i^t'(x_i^t)$ . Cost,  $C_i^t(x_i^t)$ , is expressed in million USD per year. The amount of permits held,  $x_i^t$  is expressed by million tons Carbon per year.

The global interest rate assumed throughout the simulations is of 5 % p.a. and the discount factor is then:  $\rho = \left(\frac{1}{1+0,05}\right)^5 = 0,784$  for each commitment period. This is represented in the GAMS program as a scalar D.

<sup>6</sup> In the following, \$ represents constant USD of 1997, following Godal and Klaasen (2006). M is million, B is billion, t is a metric ton, C is Carbon and yr is year.



#### 4.1.2 Business-As-Usual demand

The Business-As-Usual demand (BAU) shown in Table 4.4 are calculated in the event of no restrictions on emission, which would mean that the participants would stabilize emission at a level where the reduced cost of emitting one more unit of pollution is equal to zero. Remembering our marginal cost function from (4.2):  $C_i'(x_i^t) = -\beta_i^t + \delta_i^t x_i^t$  and inserting  $C_i'(x_i^t) = 0$ , this implies a BAU emission level of:  $x_i^t = \frac{\beta_i^t}{\delta_i^t}$ .

**Table 4.4: Business-As-Usual Emissions (MtC/yr)**

	<i>1990<sup>a</sup></i>	<i>2010</i>	<i>2015</i>
Usa	1345	1820	1914
Oecde	934	1039	1072
Japan	274	350	352
Canz	217	313	319
Eefsu	1337	899	946
China	620	1182	1309
India	153	309	344
Mopec	309	445	475
Row	646	1072	1217
<b>Total</b>	<b>5835</b>	<b>7429</b>	<b>7949</b>

<sup>a</sup> The 1990 column is the actual emission for this year.

A comment on notation: All emissions are reported as million tons (metric) carbon per year (MtC/yr). MtC/yr is a common way of reporting emission, but another widely used notation is Mt CO<sub>2</sub>/yr. To convert from carbon to CO<sub>2</sub>, we need to relate to the ratio of the atomic mass of a carbon dioxide molecule to the atomic mass of a carbon atom (44/12). In other words, the USA 1990 emission of Carbon, 1345 MtC/yr equals  $1345 \cdot (44/12) = 4932$  Mt CO<sub>2</sub>/yr.<sup>7</sup>

<sup>7</sup> For more information on conversion, see: <http://www.epa.gov/OMS/climate/420f05002.htm#converting>

## 4.2 The Scenarios

The three scenarios that will be used as a base for the following simulations are made by me as an estimate of what could possibly be expected as a Post-Kyoto agreement (2013-2017). It is important to emphasize that it is impossible to know at this stage what will be agreed upon at the Conference of Parties (COP 15) meeting in Copenhagen 2009 where a new agreement is scheduled to be finalized. Just over the past decade politicians' views on the questions regarding climatic change has evolved a lot, and to say today that any prediction made on the possible outcome of the Post-Kyoto negotiations is realistic, would be naive. I have however tried to take into consideration the different aspects of the current political debate when shaping these Post-Kyoto scenarios.

In the following, the endowments consist of permits that each allow the emission of 1 MtC/yr.

**Table 4.5: Endowments in Kyoto, Scenarios and BAU emission<sup>a</sup> (MtC/yr)**

	<i>Kyoto 08-12 (BAU 2010)</i>	<i>“5% scenario” 13-17 (BAU 2015)</i>	<i>“10% scenario” 13-17 (BAU 2015)</i>	<i>“World scenario” 13-17 (BAU 2015)</i>
USA				1345 (1914)
OECD	860 (1039)	860 (1072)	841 (1072)	794 (1072)
Japan	258 (350)	258 (352)	247 (352)	233 (352)
CANZ	215 (313)	215 (319)	195 (319)	184 (319)
EEFSU	1314 (899)	1314 (946)	1203 (946)	946 (946)
China				1309 (1309)
India				344 (344)
<b>Total</b>	<b>2647 (2601)</b>	<b>2647 (2689)</b>	<b>2486 (2689)</b>	<b>5155 (6257)</b>

<sup>a</sup> BAU emission is reported in parenthesis.

From table 4.5 the “hot air” from Eastern Europe and Former Soviet Union becomes apparent in the Kyoto period when comparing with the BAU-numbers. 46 MtC/yr are endowed above the demand for permits without any restrictions. No “hot air” is endowed in the scenarios for the next commitment period.

The scenarios shown in table 4.5 and can be categorized:

- *The “5% scenario”*: Kyoto over again. In this scenario, no new regions join the present Kyoto countries (excluding USA) in committing to abatement goals. No further abatement goals are set, they are stabilized at an average of 5% below 1990-emission level.
- *The “10% scenario”*: The same as “5% scenario”, but in this scenario the existing participants agree to abate 10% of 1990-emission level in the second commitment period (2013-2017).
- *The “World scenario”*: USA, China and India agrees to take on emission targets in the second commitment period and thus joins the emission trading scheme. OECD, CANZ, and Japan set their emission goals at 15% below 1990-emission levels. USA joins, setting their target at their 1990-emission level. EEFSU, China and India set their targets at their Business-As-Usual level (BAU 2015).

The rationale for the “World scenario” assumptions is that in the EU-region there is an ambition of a 20% abatement by 2020, which will mean close to a 15% goal by 2017. This was adopted as official policy on January 23, 2008<sup>8</sup>. It is unlikely that the European countries will accept to commit to these goals without the other regions participating today setting the same goals. In addition to this, it is unlikely that they will accept this without USA accepting abatement targets. If USA joins, it is likely that they will not accept the same rigorous goals as the already participating Kyoto nations.

US emissions were in 2005 already 16,3% above 1990-emissions, according to the UNFCCC<sup>9</sup>, and thus to set the goal at 1990-level would mean a quite ambitious goal in itself. To abate yet another 15% below 1990-level would mean a real cut of more than

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<sup>8</sup> [http://ec.europa.eu/environment/climat/climate\\_action.htm](http://ec.europa.eu/environment/climat/climate_action.htm). The 15% abatement target by 2017 is deduced by me seeing that the EU has adopted a target of 8% abatement by 2012 through the Kyoto Protocol, and 20% in 2020, which would put the average target at the end of 2017 to approximately 15%.

<sup>9</sup> [http://unfccc.int/ghg\\_emissions\\_data/ghg\\_data\\_from\\_unfccc/time\\_series\\_annex\\_i/items/3841.php](http://unfccc.int/ghg_emissions_data/ghg_data_from_unfccc/time_series_annex_i/items/3841.php)

30% from today to 2017, which in my opinion appear unrealistic. It is however likely that the USA will accept some reductions, as all the three front runners for the presidential elections in November 2008 are positive to participating in a binding agreement (Point Carbon, 2007).

The main caveat for US acceptance of abatement targets will be that China also agrees to take on emission goals. China will probably not join without the other main emitter in the region, India, agreeing to join. Thus the most likely outcome with US participation also includes these two countries.

The arguments being presented by both China and India in the ongoing discussions are however that they, as developing countries, should be given the possibilities to develop like the already industrialized part of the world. This is why I have granted them endowments equal to their BAU emissions in 2015.

The former Soviet Union countries, EEFSU, have been given a lot of “hot air” in the present Kyoto agreement. In 2005 Russia’s emission level was already 28,7% below 1990-levels, according to UNFCCC, so giving them a 15% reduction goal would mean putting more “hot air” into the market. The other large contributor to the “hot air” problem in the present agreement, Ukraine, was in 2005 already 55% below their 1990-level. It is unlikely that the other participants will accept letting these countries increase their emission levels, and so giving them BAU emissions of 2015 actually means stabilizing them at a 30% reduction or more from 1990-levels.

A comment should be made about the fact that of the Annex 1 countries not only USA, but also Australia did not ratify the Kyoto Protocol. After their November 24<sup>th</sup> 2007 election however, the new prime minister Kevin Rudd made it clear they would ratify the existing agreement, and also participate in the talks towards a new agreement.<sup>10</sup> At the Conference of Parties summit at Bali in December 2007 (COP 13) Australia in fact ratified the Protocol.

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<sup>10</sup> <http://www.guardian.co.uk/world/2007/nov/26/australia.climatechange>

As we can see from the BAU 2015 emissions in table 4.4, the residual emission from row (rest of the world) and mopec (middle east and opec) - the non-participating parties in the “World scenario” - is 1692 MtC/yr, or 21% of global emissions. Most of these countries have already ratified the present Kyoto Protocol, and if there is a post-Kyoto agreement, more of these countries could also be taking on emission reduction commitments.

Due to the relative sizes of the emissions from the other potential committers to the “World scenario” agreement, this has not been taken into consideration in these simulations in order to be able to follow the MERGE regional setup.

### 4.3 Numerical Results

The model presented in (3.17)-(3.23) has in this section been programmed in the General Algebraic Modeling System (GAMS) using the Mixed Complimentary Problems (MCP) solver. In the appendix the GAMS transcript of the “world scenario” is included. The other scenarios are simulated in the same way.

The reason for using the MCP solver is simply that this allows me to program the first order conditions instead of the objective function. In my model this is an advantage due to the properties of my marginal cost function (4.3).

The results are presented with and without banking in order to isolate the effect of the banking. GAMS reports that all banking is done by one region. The reason for this reporting, as I have explained throughout the presentation in chapter 3, is that banking has no unique individual solutions in my model, and is only unique in aggregate terms.

#### 4.3.1 The “5% scenario”

**Table 4.6: The “5% scenario” Emission and trade (MtC/yr)**

	With banking					Without banking			
	Emission <sup>a</sup>		Trade <sup>b</sup>		s	Emission <sup>a</sup>		Trade <sup>b</sup>	
	2008-12	2013-17	2008-12	2013-17		2008-12	2013-17	2008-12	2013-17
OECD	1039	1072	221	170	42	1039	1058	179	198
Japan	350	352	92	94	0	350	347	92	89
CANZ	313	319	98	104	0	313	311	98	96
EEFSU	899	946	-411	-368	0	899	931	-369	-383
<b>Total:</b>	<b>2601</b>	<b>2689</b>	<b>0</b>	<b>0</b>	<b>42</b>	<b>2601</b>	<b>2647</b>	<b>0</b>	<b>0</b>
<b>10yr Total</b>	<b>26 450 MtC</b>					<b>26 240 MtC</b>			

<sup>a</sup> The amount of emission permits each region holds on average per year over the two 5-year periods,  $x_i^t$ .

<sup>b</sup> For the first period:  $(x_i^1 - e_i^1 + s_i)$  and for the second period  $(x_i^2 - e_i^2 - s_i)$ . If the number in this column is positive, it means that the region is a net buyer of permits.

If the Post-Kyoto agreement is the same as the Kyoto agreement, with the same regions participating, our model gives an interesting, yet expected result. From table 4.5 we saw that there were 46 permits in excess in the Kyoto period and the amount of permits saved from the first period to the second is only 42. The reason is that only 42 MtC/yr is needed in the second period to fulfill the Business-As-Usual (BAU) demand for permits there as well. Four excess permits are held in period 1, but not saved.

The overall endowments across both periods exceeds the overall BAU demand for permits across the two periods. This is “hot air” from the EEFSU region. The emission data from UNFCCC confirms this, showing that 2005 emissions for Russia is already 28,7% below their 1990-emission level.

In a situation like this the model from chapter 3 will not be able to give unique individual solutions for the amount of permits demanded. The reason is simple: The price collapses, as shown in table 4.7, and the last four permits have no cost minimizing effect. From the model, it means that the endowments puts the participants at a level of emissions where marginal abatement cost is zero, and thus emissions stay at BAU level. The results tell us how much emissions each participant will have in the two periods (BAU 2010 and BAU 2015), but not who will hold the last four permits, since they will not be used. I have reported that EEFSU holds them.

It is important to emphasize that this of course is assuming no strategic behavior.

In the non-banking version of the model, we see that there will be a market in the second period, as the BAU emissions grows, but not the amount of permits, and no permits can be brought forward from the first period. In the Kyoto period of this market, the same situation arises as for the banking market; the individual holdings of permits is not known uniquely (many solutions satisfies the model) since the amount of permits endowed exceeds the BAU demand for permits. I have assumed that EEFSU holds all of the 46 surplus permits.

Notice that total amount of permits held across the 10 years is larger in the banking version than in the non-banking version. The difference is 26 450 MtC – 26 240 MtC = 210 MtC. This can thus be contributed to the “hot air” since this is amount matches exactly the saving reported, 42 MtC/yr \* 5 yr = 210 MtC. In other words: Due to the “hot air”, less abatement is done with banking than without when abatement targets and participants are the same as in the Kyoto period.

**Table 4.7: "5% scenario" Price and cost**

	With banking						Without banking					
	MAC <sup>a</sup> (\$/tC)		Cost (M\$/yr)				MAC <sup>a</sup> (\$/tC)		Cost (M\$/yr)			
	-C'1	-dC'2	C1	d*C2	trade	total/2 <sup>b</sup>	-C'1	-dC'2	C1	d*C2	trade	total/2 <sup>b</sup>
OECD	0	0	0	0	0	0	0	13	0	87	2 574	1 331
Japan	0	0	0	0	0	0	0	13	0	35	1 157	596
CANZ	0	0	0	0	0	0	0	13	0	51	1 248	649
EEFSU	0	0	0	0	0	0	0	13	0	97	-4 979	-2 441
<b>Price</b>	<b>0</b>	<b>0</b>					<b>0</b>	<b>13</b>				
<b>Total</b>			<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>			<b>0</b>	<b>270</b>	<b>0</b>	<b>135</b>

<sup>a</sup> The marginal cost of abatement is reported for both periods, and for the second period it is discounted.

<sup>b</sup> The total abatement cost columns in these tables are reported per year. In order to have the total row to follow this, I have summed the average from each period with the trade cost, and then divided this by the two periods: Total/2= (C1+d\*C2+trade)/2. Trade cost is, as discussed in chapter 3, reported across the two periods since we do not know individual trade in each period.

Table 4.7 shows that the permit price is zero in the banking version of the market. This is because of the “hot air” the EEFSU region has been granted in the Kyoto period. They have enough endowments to cover all their own BAU emissions, and all the other regions’ BAU emissions, in both periods.

It is therefore no surprise that the cost of the “5% scenario” is zero for all, as long as the market is efficient.

If we did not have banking, we see that in second period, the BAU demand is higher than the endowments, and a market price of 13 \$/tC would result. As expected, only EEFSU makes a profit as they are the only net contributors in the market. Their profit in a non-



banking version of this scenario would be 2,4 B\$/yr. The total cost of the agreement without banking would be 135 M\$/yr.

### 4.3.2 The “10% scenario”

**Table 4.8: “10% scenario” Emission and trade (MtC/yr)**

	With banking					Without banking			
	Emission <sup>a</sup>		Trade <sup>b</sup>		s	Emission <sup>a</sup>		Trade <sup>b</sup>	
	2008-12	2013-17	2008-12	2013-17		2008-12	2013-17	2008-12	2013-17
OECD	1022	1038	265	94	103	1039	1002	179	161
Japan	344	341	86	94	0	350	330	92	83
CANZ	299	299	84	104	0	313	279	98	84
EEFSU	879	911	-435	-292	0	899	875	-369	-328
<b>Total:</b>	<b>2544</b>	<b>2589</b>	<b>0</b>	<b>0</b>	<b>103</b>	<b>2601</b>	<b>2486</b>	<b>0</b>	<b>0</b>
<i>10yr Total</i>	<i>25 665 MtC</i>					<i>25 435 MtC</i>			

<sup>a</sup> The amount of emission permits each region holds on average per year over the two 5-year periods,  $x_i^t$ .

<sup>b</sup> For the first period:  $(x_i^1 - e_i^1 + s_i)$  and for the second period  $(x_i^2 - e_i^2 - s_i)$ . If the number in this column is positive, it means that the region is a net buyer of permits.

In Table 4.8 the “10% scenario” is presented, which includes the same regions as in the “5% scenario”, but with a more ambitious target of abatement at 10% below 1990-emission level in the second period.

Notice that in the non-banking version of the market, the same amount of permits are demanded in the first period as in the “5% scenario”. The reason is obvious: It is exactly the same market as in the first scenario. In the banking version, endowments in the first period are also the same, but as the model has been developed in chapter 3, we know that the way the regions behave in this period is affected by the design of the scenario, due to banking. Thus more permits are saved for the next period, and more abatement is done in the first period in this scenario than the previous one.

One of the effects of allowing banking seems to be that more abatement is done in the first period compared to the non-banking version of the same scenario. Intuitively it is

reasonable to believe that this amount of increased emission abatement matches the amount of permits saved, but the amount of abatement shifted from the second period to the first due to banking is actually less than the 103 MtC/yr saved.

Comparing with the non-banking version, we see that the real shift in abatement is  $103 \text{ MtC/yr} - 46 \text{ MtC/yr} = 57 \text{ MtC/yr}$ . This is because without banking, there would already be 46 permits in excess, meaning that 46 MtC/yr endowed would never have been emitted anyhow, due to “hot air” in EEFSU. All of these permits are saved, since the second period endowments are stricter.

As in the previous scenario, also here total abatement in the banking version is less than in the non-banking version. And yet again, it is explained by the “hot air”. Finding the difference:  $25\,665 \text{ MtC} - 25\,435 \text{ MtC} = 230 \text{ MtC}$ , which is more than in the first scenario, due to the fact that this time, all the 46 MtC/yr that are in excess each year of the Kyoto period are saved.  $46 \text{ MtC/yr} * 5 \text{ yr} = 230 \text{ MtC}$ .

**Table 4.9: "10% scenario" Price and cost**

	With banking						Without banking					
	MAC <sup>a</sup> (\$/tC)		Cost (M\$/yr)				MAC <sup>a</sup> (\$/tC)		Cost (M\$/yr)			
	-C'1	-d*C'2	C1	d*C2	trade	total/2 <sup>b</sup>	-C'1	-dC'*2	C1	d*C2	trade	total/2 <sup>b</sup>
OECD	30	30	250	507	10 770	5 764	0	61	0	2 136	9 821	5 978
Japan	30	30	92	169	5 400	2 830	0	61	0	677	5 063	2 870
CANZ	30	30	209	307	5 640	3 078	0	61	0	1 214	5 124	3 169
EEFSU	30	30	303	525	-21 810	-10 491	0	61	0	2 161	-20 008	-8 923
<b>Price</b>	<b>30</b>	<b>30</b>					<b>0</b>	<b>61</b>				
<b>Total</b>			<b>854</b>	<b>1 509</b>	<b>0</b>	<b>1 181</b>			<b>0</b>	<b>6 188</b>	<b>0</b>	<b>3 094</b>

<sup>a</sup> The marginal cost of abatement is reported for both periods, and for the second period it is discounted.

<sup>b</sup> The total abatement cost columns in these tables are reported per year. In order to have the total row to follow this, I have summed the average from each period with the trade cost, and then divided this by the two periods:  $\text{Total}/2 = (C1 + d*C2 + \text{trade})/2$ . Trade cost is, as discussed in chapter 3, reported across the two periods since we do not know individual trade in each period.

As expected, in this second scenario we see that there is a positive price for emission permits in the banking version of the market as well. The price of 30 \$/tC means that for all the regions involved, it is beneficial to abate more in the first period of this scenario

than in the “5% scenario”. We see from tables 4.6 and 4.8 that this in fact happens. The reason is that abating today means more excess permits to save for the next period, so the participants can better smooth their costs so that the emission is done when of least cost.

What also becomes apparent here as well is that banking shaves costs. Across the two periods, the banking version of “10% scenario” cost 1,2 B\$/yr while the non-banking version cost 3,1 B\$/yr or 158% more. The explanation mirrors the argument above; due to cost smoothing, abatement is not only done where it is of least cost, but also when it is of least cost.

The overall abatement cost reduction due to banking is in this scenario 3,1 B\$/yr – 1,2 B\$/yr = 1,9 B\$/yr. Remembering that the increased emissions due to banking was 46 MtC/yr, we see that each ton increase in Carbon emission per year caused by banking, saves 41 USD.

The Kyoto period of the non-banking version is once again equal to the same period in the first scenario. This means that the same “hot air” is floating around in the market, giving everyone enough endowments to go around, while in the stricter Post-Kyoto period, abatement must happen and the cost of compliance rise. The permit price is also double that of the banking market in the second non-banking period.

Another interesting point to be made is that in this banking version, the profit EEFSU is making, 10,5 B\$/yr, is almost equal to the aggregated cost of the rest of the regions (11,7 B\$/yr). It is also noticeable that the aggregate cost of the agreement across all regions is less than the individual cost for any of the participants, excluding EEFSU.

Finally, it is worth remembering that in (3.6) the saving is added in the first period and subtracted in the second. Both times it is multiplied by the same price (in the case where we actually have saving). This explains why, in the cost tables, banking is not included, since across the two periods, the banking cancels itself out. Still, its effects are apparent enough through the abatement, overall cost and price of permits.

### 4.3.3 The “World scenario”

**Table 4.10: "World scenario" Emission and trade (MtC/yr)**

(MtC/yr)	With banking					Without banking			
	Emission <sup>a</sup>		Trade <sup>b</sup>		s	Emission <sup>a</sup>		Trade <sup>b</sup>	
	2008-12	2013-17	2008-12	2013-17		2008-12	2013-17	2008-12	2013-17
USA	1820	1586	0	241	0	1820	1497	0	152
OECD	982	955	357	-74	235	1039	923	179	129
Japan	329	316	71	83	0	350	306	92	73
CANZ	267	251	52	67	0	313	233	98	49
EEFSU	834	827	-480	-119	0	899	794	-369	-152
China	1182	1168	0	-141	0	1182	1130	0	-179
India	309	287	0	-57	0	309	272	0	-72
<b>Total:</b>	<b>5723</b>	<b>5390</b>	<b>0</b>	<b>0</b>	<b>235</b>	<b>5912</b>	<b>5155</b>	<b>0</b>	<b>0</b>
<b>10yr Total</b>	<b>55 565 MtC</b>					<b>55 335 MtC</b>			

<sup>a</sup> The amount of emission permits each region holds on average per year over the two 5-year periods,  $x_i^t$ .

<sup>b</sup> For the first period:  $(x_i^1 - e_i^1 + s_i)$  and for the second period:  $(x_i^2 - e_i^2 - s_i)$ . If the number in this column is positive, it means that the region is a net buyer of permits.

In this final scenario, three new regions are included in the market in the second period: USA, China and India. Observe that they are given their Business-As-Usual demands as endowment and emission in the first period, but are restricted from trading. This is done for programming purposes.

In this scenario 235 MtC/yr is saved. This is substantial, and even taking away the surplus endowments (46 MtC/yr), this means 189 MtC/yr is abated in the first period solely due to banking. A considerable shift of abatement almost the size of CANZ entire 1990-emissions, and more than India’s 1990-emissions, every year.

In this scenario for the first time, other regions than EEFSU are net contributors of permits. Both China and India joins EEFSU as the providers of permits in the market. However, it is worth noticing that neither China nor India has been granted any “hot air”, as EEFSU has in the first period. Actually, they have only been granted their BAU demand. This follows our theory; even though no restrictions are put on these countries, they still choose to sell, because they make a larger profits by selling permits and reduce

emission. This falls in line with the basic permit trade theory: the abatement is done where, and when, the cost of abatement is lowest. It is reasonable to assume that in developing economies there are more inexpensive ways of abating emission, than in more technologically advanced economies.

OECD is also a net seller in the second period of this banking market. This is due to the fact that all the saving has been attributed to them. This could have been divided among all the participants, and the results would still hold, knowing that saving cannot be known uniquely.

In the non-banking version of the market, all of the net contributors to the market sell more permits than in the banking version. The main explanation for this is that since no permits are being brought into the market from the previous period, the demand is higher relative to supply than in the banking-market. We also see, as expected, that in the non-banking market, more abatement is done in the second period than in the same period in the banking version.

And finally, once again we see that total emissions across the two periods in the banking version is higher than total emissions in the non-banking version of the market. Not surprisingly, the difference over the 10 yr period is 230 MtC, which, as in the “10% scenario”, is equal to the sum of the five years of “hot air” excess endowments.

The banking mechanism does however shift the abatement so that isolated to the first period, the banking version provides more abatement.

**Table 4.11: "World scenario" Price and cost**

	With banking						Without banking					
	MAC <sup>a</sup> (\$/tC)		Cost (M\$/yr)				MAC <sup>a</sup> (\$/tC)		Cost (M\$/yr)			
	-C'1	-dC'2	C1	d*C2	trade	total/2 <sup>b</sup>	-C'1	-dC'2	C1	d*C2	trade	total/2 <sup>b</sup>
USA	0	102	0	16 779	24 582	20 681	0	130	0	27 108	19 760	23 434
OECD	102	102	2 905	5 952	28 866	18 861	0	130	0	9 645	16 770	13 208
Japan	102	102	1 097	1 814	15 708	9 310	0	130	0	2 963	9 490	6 226
CANZ	102	102	2 317	3 493	12 138	8 974	0	130	0	5 578	6 370	5 974
EEFSU	102	102	3 280	6 069	-61 098	-25 874	0	130	0	9 902	-19 760	-4 929
China	0	102	0	7 228	-14 382	-3 577	0	130	0	11 643	-23 270	-5 814
India	0	102	0	2 904	-5 814	-1 455	0	130	0	4 641	-9 360	-2 359
<b>Price</b>	<b>102</b>	<b>102</b>					<b>0</b>	<b>130</b>				
<b>Total</b>			<b>9 599</b>	<b>44 239</b>	<b>0</b>	<b>26 919</b>			<b>0</b>	<b>71 480</b>	<b>0</b>	<b>35 740</b>

<sup>a</sup> The marginal cost of abatement is reported for both periods, and for the second period it is discounted.

<sup>b</sup> The total abatement cost columns in these tables are reported per year. In order to have the total row to follow this, I have summed the average from each period with the trade cost, and then divided this by the two periods:  $Total/2 = (C1 + d*C2 + trade)/2$ . Trade cost is, as discussed in chapter 3, reported across the two periods since we do not know individual trade in each period.

In the final scenario we see that not only EEFSU is making a profit in the market, but also China and India. This echoes table 4.10 where they all are net contributors to the market of emission permits.

The price of permits has risen considerably with the inclusion of the large emitters. USA puts great pressure on demand in the second period, and it makes the price surge compared to the other scenarios. In the second period of the non-banking version of the market, we see that the price rise to 130 \$/tC, while banking releases some of the pressure in the last period, where the price is 102 \$/tC. Once again it is noticeable that the aggregated cost in the banking version of the market, 26,9 B\$/yr, is less than what it would have been without banking 35,7 B\$/yr, although this time the non-banking version is only 33% more expensive. In absolute terms, a saving of 8,8 B\$/yr means that banking saves 88 B\$ across the two periods (10 years) across all participants.

In this scenario, the cost saving per extra emitted ton of Carbon per year due to banking is  $(35,7 - 26,9) \text{ B\$/yr} / 46 \text{ MtC/yr} = 191 \text{ USD/tC}$  which is considerably higher than the 41

USD/tC in the “10% scenario”. This hints towards banking being more efficient in a stricter agreement.

In contrast to the “10% scenario”, the aggregate cost of the banking market, 26,9 B\$/yr, is more than any of the individual costs. Also, EEFSU is no longer reaping all the profits. Due to the fact that China and India choose to abate rather than to utilize all of their own endowments, we see that both of these countries are making a profit as well, although considerably less than EEFSU. The latter still makes a profit that is larger than any of the other regions cost, even though they abate more emissions in both periods in this scenario.

In both the “10% scenario” and in the “world scenario” we see that the banking reduces emission in the short run (first commitment period) and makes the total cost of abatement across both periods fall. In the first period the cost of abatement is higher for the participants with banking. This is obvious, since without banking there are no costs in the first period. In the second period the cost of abatement for all is lower with banking; also intuitive considering that they abate more in the first period.

In the “10% scenario” all the participants benefit from banking across both periods; EEFSU makes more profit, and the others have lower total abatement costs. In the “world scenario”, only USA and EEFSU are better off with banking. For the others, the non-banking market actually gives them less overall cost per year, or more profit per year, in the case of China and India. A reason for this can be that the price of permits in the non-banking second period is higher. For a big permit buyer like USA, who is not participating in the market in the first period, and is thus excluded from banking, a lower price is preferred. For EEFSU, a price equal to zero in the first period means large losses, since they sell 369 permits in this period. China and India does not feel this effect, since they are only allowed to sell in the second period anyway, so they make more profit without banking.

## 5. Discussion and Limitations

The purpose of this thesis has been to numerically analyze the effect of banking on the first two commitment periods of the Kyoto Protocol. In order to do this I have presented a model on emission trade with banking across two periods and I have made assumptions regarding three scenarios of how the second period endowments can be. Finally these scenarios has been programmed in GAMS with cost functions from the MERGE model.

This analysis has important limitations: The assumptions of the model; the parameters and data I use; the fact that I have not looked at the efficiency of banking compared to a social optimum; and some limitations regarding the scenarios themselves. In the following I will briefly comment on this.

Maybe the most important weakness of the model is that it assumes no strategic behavior. As Manne and Richels (2004) point out, the majority of the “hot air” in the first commitment period is concentrated in a few countries in the EEFSU region; mainly Russia and the Ukraine. Godal and Meland (2006) investigate coalition formation in a static environment (one-period) and emphasize that there are no formal hurdles for coalition formations in the Kyoto Protocol. One of the points they make is that just as strategic behavior on the supply side can push prices up, strategic behavior on the buyer side can work in the opposite direction. They suggest gains from equilibrium cartels involving both large sellers and buyers. I will not speculate on how strategic behavior would affect my results over two periods, but taking into consideration that the first commitment period has already started, and that the second period has not yet been agreed upon, it is not controversial to assume that some strategic behavior could take place, and is worth investigating in a two period framework.

The absence of borrowing could also be discussed as a limitation of the model. However, seeing from chapter three that this would be interesting when prices fall from period 1 to period 2, and knowing that in the numerical results the permit price without banking was equal to zero, I do not consider this as of major importance in this analysis.



Regarding the parameters and data I use, the most important limitation is that they do not include non-energy related carbon emissions, non-Carbon greenhouse gas emissions and the Clean Development Mechanism. Godal and Klaassen (2006) suggest that including this would most likely contribute to a lower permit price.

Also, Manne and Richels (2004) stress that US emission in 2010 might be lower than anticipated by the MERGE model, due to the fact that the energy sector might be anticipating future emission restrictions.

As Kling and Rubin (1997) highlights, what is good for the participant in a banking model, is not always good for society. Their modified banking model restricts borrowing, as I have done. I have however not investigated whether or not a rise in the price of permits at the rate of the interest rate is socially optimal, which is what I find with banking. Comparing to environmental models it could be that in order to limit climatic change, the price should rise faster. Manne and Richels (2001) as cited in Godal and Klaassen (2006), use MERGE to investigate optimal emission paths constrained by a maximum rise of the average temperature of 2 degrees Celsius in the period 2000-2100. Their findings suggest that carbon price rises approximately by the rate of interest. This could mean that the results I find are close to efficient, but this could have been investigated more.

Another question that I do not examine is how banking affects technological development. Phaneuf and Requate (2002) find that in some cases permit banking can substitute investment spending. Their argument is that under a policy that does not allow banking, technological investments is the option they have to smooth abatement costs, and that allowing banking will lead to a suboptimal investment level.

Finally, caution has to be taken when considering the results of this thesis due to the fact that the political process leading up to the signing of new agreement is very unpredictable, and thus there is much uncertainty regarding the composition of my scenarios.

## 6. Conclusion

If shifting emission abatement forward in time is a policy objective, then banking is a valuable tool of the emission permit trade in the Kyoto framework. The caveat is that in the two period world I have simulated, the second period abatement goals need to be stricter, or more countries must accept emission targets, than in the Kyoto period. If it is not, this effect is lost.

According to the IPCC (2007), it will be important to reduce emission sooner, rather than later to prevent adverse climatic changes. Banking has the property of helping achieve this even though it takes time for national governments to accept that a price has to be paid in order to limit the effects of global warming. If large emitters do not join until a later period, the effect of a stricter agreement in this period can still lead to more abatement in the previous period when banking is allowed.

The other main conclusion from this thesis is that banking makes abatement goals achievable at a lower cost. Based on my scenarios there is a considerable cost saving element in banking for the overall compliance cost. As we have seen from the results, this is due to the cost smoothing that the participants are able to make across the two periods when banking is an option.

In the “world scenario” it is worth noting that the only two regions that were better off in the yearly average costs with banking were the USA and EEFSU. The rest of the participants were better off individually without banking. This effect is important to bear in mind when shaping the new agreement. For all participants, banking did have a smoothing effect however; costs were divided over the two periods, instead of being all in the second period, which is the case without banking.

The major profits the EEFSU is making in the banking version of the “world scenario” could become an obstacle when developing the next agreement. This profit has its roots in the “hot air” from the Kyoto agreement. Banking makes abatement happen in the first

commitment period, even though there is “hot air” in this period and is thus valuable in this regards. The financial implications this has could however in my opinion pose a serious threat to the development of the Post-Kyoto agreement due to the fact that the cost saving of banking in the “world scenario” is mainly due to the large profits EEFSU is making.

As discussed, my assumptions, the model and therefore also my simulations have important shortcomings. In particular, the numeric values for cost and abatement should be treated with much caution. Even so I am still of the opinion that these numerical results do show that banking can achieve the desired effects if a new agreement is in place.

The fact that banking has short term effects on abatement and cost saving properties overall, makes it a strong tool when going into the next commitment period, and beyond.

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## 8. Appendix

THE GAMS RUNS:

GAMS Rev 148 x86/MS Windows

03/22/08

15:11:24 Page 1

### The Post-Kyoto 3 Protocol

C o m p i l a t i o n

```
2
3 SET I Agents / China, USA, OECD, JAPAN, CANZ, EEFSU, India /;
4
5 * USA, India og Kina er bare med i andre periode
6
7
8 * Data
9
10 SCALAR D discount factor/
11
12          0.7836 /;
13
14 PARAMETER b1(i) abatement cost parameter b1 /
15 India      971 ,
16 China      1383 ,
17 USA        1003 ,
18 OECD       1883 ,
19 JAPAN      1727 ,
20 CANZ       693 ,
21 EEFSU      1410 /;
22
23 PARAMETER d1(i) abatement cost parameter d1 /
24 India      3.144 ,
25 China      1.17 ,
26 USA        0.551 ,
27 OECD       1.813 ,
28 JAPAN      4.933 ,
29 CANZ       2.216 ,
30 EEFSU      1.569 /;
31
32 PARAMETER e1(i) initial permit allocation 1 /
33 India      309 ,
34 China      1182 ,
35 USA        1820 ,
36 OECD       860 ,
37 JAPAN      258 ,
38 CANZ       215 ,
39 EEFSU      1314 /;
40
41 PARAMETER b2(i) abatement cost parameter b2 /
42 India      790 ,
43 China      1211 ,
44 USA        760 ,
45 OECD       1185 ,
46 JAPAN      1258 ,
47 CANZ       611 ,
```

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48 EEFSU      1034  /;
49
50 PARAMETER d2(i) abatement cost parameter d2 /
51 India      2.298  ,
52 China      0.925  ,
53 USA        0.397  ,
54 OECD       1.105  ,
55 JAPAN      3.574  ,
56 CANZ       1.914  ,
57 EEFSU      1.093  /;
58
59 PARAMETER e2(i) initial permit allocation 2/
60 India      344    ,
61 China      1309   ,
62 USA        1345   ,
63 OECD       794    ,
64 JAPAN      233    ,
65 CANZ       184    ,
66 EEFSU      946    /;
67
68 * Variables
69
70 POSITIVE VARIABLE
71
72          p1          permit price 1,
73          p2          permit price 2,
74          lambda(i)   shadow price on saving;
75
76 VARIABLE
77          x1(i)       final allocation 1,
78          x2(i)       final allocation 2,
79          s(i)        saving;
80
81
82 * Equations
83
84 EQUATIONS
85          FOB_x1(i)   first order condition x1,
86          FOB_x2(i)   first order condition x2,
87          FOB_s(i)    first order condition s,
88          CLEAR1      clearing condition 1,
89          CLEAR2      clearing condition 2,
90          CONSTRAINT_s(i) no-borrow condition;
91
92 FOB_x1(i)..          min( 0, -b1(i) + d1(i)*x1(i) ) + p1 =e= 0;
93
94 FOB_x2(i)..          D* min( 0, -b2(i) + d2(i)*x2(i) ) + p2 =e=
0;
95
96 FOB_s(i)..           p1 - p2 - lambda(i) =e= 0;
97
98 CLEAR1..            - sum(i, x1(i)) + sum(i, e1(i)) - sum(i,
s(i)) =e= 0;
99
100 CLEAR2..            - sum(i, x2(i)) + sum(i, e2(i)) + sum(i,
s(i)) =e= 0;
101
102 CONSTRAINT_s(i)..   s(i) =g= 0;

```





FINAL STATISTICS

Inf-Norm of Complementarity . . 1.9619e-009 eqn: (FOB\_x2(USA))  
 Inf-Norm of Normal Map . . . . 1.9619e-009 eqn: (FOB\_x2(USA))  
 Inf-Norm of Minimum Map . . . . 1.9618e-009 eqn: (FOB\_x2(USA))  
 Inf-Norm of Fischer Function. . 1.9619e-009 eqn: (FOB\_x2(USA))  
 Inf-Norm of Grad Fischer Fcn. . 1.0394e-009 eqn: (FOB\_x1(EEFSU))  
 Two-Norm of Grad Fischer Fcn. . 2.2270e-009

FINAL POINT STATISTICS

Maximum of X. . . . . 1.5863e+003 var: (x2(USA))  
 Maximum of F. . . . . 1.9619e-009 eqn: (FOB\_x2(USA))  
 Maximum of Grad F . . . . . 4.9330e+000 eqn: (FOB\_x1(JAPAN))  
 var: (x1(JAPAN))

---- EQU FOB\_x1 first order condition x1

	LOWER	LEVEL	UPPER	MARGINAL
China	.	101.988	.	1182.000 REDEF
USA	.	101.868	.	1820.000 REDEF
OECD	.	.	.	982.323
JAPAN	.	.	.	329.404
CANZ	.	.	.	266.675
EEFSU	.	.	.	833.621
India	.	102.048	.	309.000 REDEF

---- EQU FOB\_x2 first order condition x2

	LOWER	LEVEL	UPPER	MARGINAL
China	.	.	.	1168.400
USA	.	.	.	1586.322
OECD	.	.	.	954.543
JAPAN	.	.	.	315.548
CANZ	.	.	.	251.186
EEFSU	.	.	.	826.871
India	.	.	.	287.106

---- EQU FOB\_s first order condition s

	LOWER	LEVEL	UPPER	MARGINAL
China	.	.	.	.
USA	.	.	.	.
OECD	.	.	.	234.976
JAPAN	.	.	.	.
CANZ	.	.	.	.
EEFSU	.	.	.	.
India	.	.	.	.

	LOWER	LEVEL	UPPER	MARGINAL
---- EQU CLEAR1	-5958.000	-5958.000	-5958.000	102.048
---- EQU CLEAR2	-5155.000	-5155.000	-5155.000	102.048

CLEAR1 clearing condition 1  
 CLEAR2 clearing condition 2

---- EQU CONSTRAINT\_s no-borrow condition

	LOWER	LEVEL	UPPER	MARGINAL
China	.	.	+INF	.
USA	.	.	+INF	.
OECD	.	234.976	+INF	.
JAPAN	.	.	+INF	.
CANZ	.	.	+INF	.
EEFSU	.	.	+INF	.
India	.	.	+INF	.

	LOWER	LEVEL	UPPER	MARGINAL
---- VAR p1	.	102.048	+INF	.
---- VAR p2	.	102.048	+INF	.

p1 permit price 1

p2 permit price 2

---- VAR lambda shadow price on saving

	LOWER	LEVEL	UPPER	MARGINAL
China	.	.	+INF	.
USA	.	.	+INF	.
OECD	.	.	+INF	234.976
JAPAN	.	.	+INF	.
CANZ	.	.	+INF	.
EEFSU	.	.	+INF	.
India	.	.	+INF	.

---- VAR x1 final allocation 1

	LOWER	LEVEL	UPPER	MARGINAL
China	1182.000	1182.000	1182.000	101.988
USA	1820.000	1820.000	1820.000	101.868
OECD	-INF	982.323	+INF	.
JAPAN	-INF	329.404	+INF	.
CANZ	-INF	266.675	+INF	.
EEFSU	-INF	833.621	+INF	.
India	309.000	309.000	309.000	102.048

---- VAR x2 final allocation 2

	LOWER	LEVEL	UPPER	MARGINAL
China	-INF	1168.400	+INF	.
USA	-INF	1586.322	+INF	.
OECD	-INF	954.543	+INF	.
JAPAN	-INF	315.548	+INF	.
CANZ	-INF	251.186	+INF	.
EEFSU	-INF	826.871	+INF	.
India	-INF	287.106	+INF	.

---- VAR s saving

	LOWER	LEVEL	UPPER	MARGINAL
China	-INF	.	.	.
USA	-INF	.	.	.
OECD	-INF	234.976	+INF	.
JAPAN	-INF	.	+INF	.
CANZ	-INF	.	+INF	.
EEFSU	-INF	.	+INF	.
India	-INF	.	.	.

```

**** REPORT SUMMARY :
0      NONOPT
0 INFEASIBLE
0 UNBOUNDED
3 REDEFINED (REDEF)
0      ERRORS

```