ON MULTI-PERIOD ALLOCATION OF TRADABLE EMISSION PERMITS

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Abstract

Economic analysis of emission permit markets, and particularly of the initial permit allocation, have concentrated largely on static approaches. This is somewhat unsatisfactory as the allocation method in subsequent commitment periods may influence the behaviour of the market participants in the current period. For instance, some advocate a system of "rolling grandfathering", in which later period allocations would be based on the actual (rather than allotted) emissions in earlier periods. Alternatively, emission permits can be allocated on the basis of the distance between actual and desired emission intensities in previous periods. This paper analyses the dynamic aspects of allocating greenhouse gas emission rights for different approaches using multi-player/two-period models. We show that different future allocation approaches create different strategic incentives at present, and that the permit market may partially or completely offset these incentives. We also demonstrate under what circumstances dynamic allocation rules create incentives to (lobby for) accelerating or decelerating emission reduction paths. Allowing for intertemporal transfer of abatement activities (banking and borrowing), the net present costs can be reduced. However, whether banking or borrowing is beneficial for a company depends not only on their own abatement costs and that of other companies trading permits on the market, but also on the allocation mechanism implemented**.**

Keywords: banking and borrowing, emission permits, permit allocation, dynamic approach

JEL Classification: Q25, Q28

1 Introduction

Much has been said and written about markets of emission permits, and this is particularly true for the initial allocation of emission permits (see e.g. Woerdman, 2000; or Harrison and Radov, 2002). In a sense, emission permits are property rights and introducing them has implications for the distribution of wealth. However much attention has been paid to the *initial* allocation, there is little attention to the allocation of permits in later periods – and less to the effect this may have on the behaviour of the market in earlier periods. This paper seeks to fill this gap.

We set up an analytically tractable model of an emission permit market, for concreteness referring to the market of carbon dioxide, and contrast three dynamic allocation rules and two mechanisms to steer overall emission reduction. The first dynamic allocation rule is in fact static: Allocations depend on emissions in the period before emission reduction. The other two rules are truly dynamic. In one, allocations depend on actual emission in the previous period. In the other, allocations depend on the emission reduction effort in the previous period. We also contrast the situation in which the regulator sets the overall emission target with the situation in which the regulator sets the price of emission reduction. In a static model, the two strategies are equivalent (under perfect information but not under uncertainty, see Weitzman, 1974). However, in a dynamic model, they are not. Furthermore, we investigate the effect that banking and borrowing may have on the above.

Various authors have addressed problems of the initial allocation of emission permits. Woerdman (2000), for example, analyses the issue of permit allocation as a major political barrier to establish an (inter)national emissions trading scheme. Holmes and Friedman (2000) present different design alternatives for a domestic trading scheme in the U.S. Viguier (2001) discusses diverse allocations of emission allowances across Member States of the European Union. Woerdman (2001) considers under which conditions European differences in domestic permit allocation procedures will lead to competitive distortions (see also OECD, 1999; Zhang, 1999) and result in state aid. Most recently, Cramton and Kerr (2002) analysed the distributional implications of allocating CO_2 permits through auctions. Mindful of political economy problems they argue that auctioning is superior to grandfathering. Harrison and Radov (2002) evaluate the different allocation mechanism for the European Union.

Approaches using numerical simulations to evaluate methods of allocating permits have largely concentrated on static approaches. Edwards and Hutton (2001) use a computable general equilibrium model to assess different allocation methods for the UK. Burtraw *et al.* (2002) apply an electricity market simulation model to compare three different allocation mechanism for the US. Others including pre-existing distortions in their analysis for the U.S. are Goulder *et al.* (1999).

All analysis find that auctioning the permits and using the revenue to reduce distorting taxes are the cheaper method compared to grandfathering or output-based allocation. Burtraw *et al.* (2002) discover that auctioning might even be preferable to owners of existing generation assets. However, Stavins (1998) points out that wherever tradable permits have been adopted, the initial allocation of permits has always been through grandfathering rather than through other methods. These findings are supported by Schwarze and Zapfel (2000) who stress the conflict between efficiency and political acceptability. They investigated on the design of the two most prominent U.S. cap-and-trade programs (US EPA Sulfur Allowance Trading Program and South Californian Regional Clean Air Incentives Market (RECLAIM). According to the EU Directive (EU Commission, 2003) for establishing a community wide emissions trading, 95 per cent of the allowances shall be allocated free of charge for the first commitment period.

Our paper is different. We investigate the effect of different *dynamic* permit allocation approaches on the behaviour of the market. Dynamic allocation obviously interact with trading over time, better known as banking and borrowing, which we consider explicitly. To our knowledge, only two other studies take into account dynamic effects of permit allocation. Böhringer and Lange (2003) show that dynamic allocation schemes as discussed here cannot be optimal, but they also derive conditions for second-best dynamic allocations. They consider emission-based allocations, which corresponds to our rolling grandfathering, and output-based allocations, which corresponds to our technology standards. Böhringer and Lange do not investigate the permit market in detail, as we do in this paper. Jensen and Rasmussen (2000) use a dynamic multi-sectoral model of the Danish economy to investigate the effects of different allocation approaches on welfare, CO_2 leakage, employment and stranded costs. They compare auctioning to grandfathering and an output-based allocation depending on a company's market share. In neither Jensen and Rasmussen (2000) nor Böhringer and Lange (2003) intertemporal transfer of permits is considered. We contrast and compare two alternative dynamic allocation approaches (rolling grandfathering and technology standards) and include intertemporal transfer of permits in the analysis.

Although banking and/or borrowing are an integral part of most policy programs, it is only recently that economists started to formally investigate its aspects. Theoretical analysis are e.g. Cronshaw and Kruse (1996) who examine a competitive intertemporal model for bankable emission permits. Rubin (1996) uses a continuous time model of banking and borrowing and derives permit prices and emission paths. Kling and Rubin (1997) use a similar framework to examine the efficiency properties of a permit banking system. The results indicate that allowing banking reduces the costs of emission reduction. However, Kling and Rubin (1997) found firms choosing excessive damage and output levels in early periods in a system allowing for banking and borrowing. Extending their analysis to include stock pollutants, Leiby and Rubin (2001) show that environmental regulation can achieve the socially optimal level of emissions. Godby *et al*. (1997) extend the analysis to uncertainty in the control of emissions. In an experimental setting they find banking improving price stability substantially. Steenberghe (2002) analysis the effect of banking under the Kyoto Protocol on the world emissions, abatements costs and the permit price for different scenarios. Hagem and Westskog (1998) explore the optimal design of an intertemporal trading system with banking and borrowing under market imperfections. None of the above mentioned analyses combine dynamic permit allocation approaches with intertemporal transfer of permits.

The paper is structured as follows: Sections 2 starts with a stylised model of a two period market for tradable permits. Section 3 extends the model to include different emission allocation approaches: rolling grandfathering and technology standards. Section 4 contrasts a policy based on quantities (as in Sections 2, 3, 5 and 6) with a policy based on prices. Sections 5 and 6 introduce intertemporal banking and borrowing of emission permits, and examine the consequences for the different permit allocation approaches. Section 7 concludes.

2 The market

Let us consider a two-period market for tradable permits with *I* companies. Permits cannot be transferred between periods. Emission reduction costs *C* are quadratic (this, restrictive, assumption makes the model analytically tractable). Each company solves the problem:

$$(1)\quad \min_{R_{i1},R_{i2},P_{i1},P_{i2}} C_i = \alpha_{i,1}R_{i,1}^2 + \frac{\alpha_{i,2}R_{i,2}^2}{1+\delta} + \pi_1 P_{\mathrm{i},1} + \frac{\pi_2 P_{\mathrm{i},2}}{1+\delta} \text{ s.t. } R_{i,1} + P_{i,1} \geq E_{i,1} - A_{i,1}; R_{i,2} + P_{i,2} \geq E_{i,2} - A_{i,2}$$

R is emission reduction; *α* is a parameter; *δ* is the discount rate; *P* denotes the amount of emission permits bought or sold; *π* is the emission permit price; assuming a perfect market, all companies face the same price; *E* are the emissions; *A* are the allocated emission permits; that is, if a company emits more than has been allocated, *E*>*A*, it will have to reduce emissions or buy permits on the market.

The first order conditions of (1) are:

$$(2a)\quad \frac{2\alpha_{i,t}R_{i,t}}{(1+\delta)^{t-1}} - \lambda_{i,t} = 0, i = 1,2,...,I, t = 1,2$$

$$(2b)\quad \frac{\pi_t}{(1+\delta)^{t-1}} - \lambda_t = 0, i = 1,2,...,I, t = 1,2$$

$$(2c)\quad R_{i,t} + P_{i,t} - E_{i,t} + A_{i,t} = 0, i = 1,2,...,I; t = 1,2$$

where *λ* denotes the LaGrange multiplier. Note the Hotelling nature of (2b). This is a system with 6*I* equations and 6*I*+2 unknowns, but we also have

$$(2d)\quad \sum_{i=1}^{I} P_{i,t} = 0, t = 1,2$$

(2) solves as:

$$(3a)\quad \pi_t = \lambda_{i,t} = \frac{\sum_{i=1}^{I}(E_{i,t} - A_{i,t})}{\sum_{i=1}^{I} 1/2\alpha_{i,t}}$$

$$(3b)\quad R_{i,t} = \frac{\pi_t}{2\alpha_{i,t}}$$

$$(3c)\quad P_{i,t} = E_{i,t} - A_{i,t} - \frac{\pi_t}{2\alpha_{i,t}}$$

So, the permit price goes up if the emission reduction obligation increases or if the costs of emission reduction increase. All companies face the same marginal costs of emission reduction, and the trade-off between reducing emissions in-house and buying or selling permits is driven by the ratio of marginal emission reduction costs and the permit price. As there is no banking and borrowing, the markets in the two periods are independent and the discount rate does not influence the result. The modelled market behaves as expected. Rehdanz and Tol (2002) consider the special case *I*=2 for one period only.

3 Dynamic allocation

3.1 Alternative allocations

Let us assume that the emission reduction obligations in the first period are based on grandfathering. For example, all companies should reduce a fixed percentage τ (with $0< \tau<1$) of their emissions E in period 0, $A_{i,1}=E_{i,0}-(1-\tau_1)E_{i,0}=\tau_1 E_{i,0}$.[1]

The second period is more interesting. In (1), we assume that the emission allocation in period 2 is independent of what happens in period 1. For instance, the allocation may be based on the emissions of period 0, $A_{i,2}=\tau_2 E_{i,0}$. In the long run, a system of "fixed grandfathering" based on the period before emission reduction policies, may lead to substantial redistributions, as the emission allocation gets more and more out of step with actual emissions. It is therefore likely that the emission allocation in the second period somehow reflects the reality of period 1 rather than period 0.

One way in which this may happen is through a system of "rolling grandfathering" (or perhaps "updated grandfathering"), that is, emission allocation in period 2 are based on the actual emissions in period 1. That is, $A_{i,2}=\tau_2(E_{i,1}-R_{i,1})$.[2] In words, the emission reduction obligation in period 2 falls with emission reduction in period 1, or the more one reduces now, the more one has to reduce in the future. There would be less of an incentive to reduce emissions as it would only reduce the amount of permits receiving in the future. This was recently discussed by Harrison and Radov (2002).

Alternatively, emission allocations may shift away from grandfathering to technology standards. Such standards could be based on the emission intensity of the companies. Suppose that the emission allocation is based on the best available, commercially proven technology. That is, emission allocations are based on some fixed percentage of potential emissions (those emissions that would have been had the company used the best technology), except for the technology leader, whose allocation is based on actual emissions. Without loss of generality, assume that, in period 0, all companies are the same size and have a turnover of unity; further assume that they all have equal emissions (and hence emission intensities) as well, but different abatement costs. The emission allocation could then be something like $A_{i,2}=\tau_2(E_{i,1}-R_{\max,1}+R_{i,1})$. In words, the emission reduction obligation in period 2 falls with emission reduction in period 1, or the more one reduces now, the less one has to reduce in the future.

For rolling grandfathering, (1) changes to:

$$(4)\quad \min_{R_{i1},R_{i2},P_{i1},P_{i2}} C_i=\alpha_{i,1}R_{i,1}^2+\frac{\alpha_{i,2}R_{i,2}^2}{1+\delta}+\pi_1 P_{i,1}+\frac{\pi_2 P_{i,2}}{1+\delta}\ \text{ s.t. } R_{i,1}+P_{i,1}\geq E_{i,1}-A_{i,1}; R_{i,2}+P_{i,2}\geq E_{i,2}-A_{i,2}$$

$$\text{with}\quad \sum_{i=1}^{I}P_{i,t}=0, t=1,2 \ \text{ and } \ A_{i,2}=\tau_2(E_{i,1}-R_{i,1})$$

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[1] Emission allocations could also be based on a company's share in the total emissions cap. If the total cap is also based on emissions in period 0, τ would be replaced by another constant, leaving the analysis unaffected.

[2] Emission allocations could also be based on a company's share in the total emissions cap. The τ would then not be constant, but a function of total emission reduction in period 1 (which is a constant) and the company's contribution to that (which is a decision variable). This would complicate the notation and the analysis without adding much insight; we in fact suspect that the two cases are equivalent.

The first order conditions are:

(5a) $2\alpha_{i,1}R_{i,1} - \lambda_{i,1} + \tau_2\lambda_{i,2} = 0, i = 1,2,...,I$

(5b) $\frac{2\alpha_{i,2}R_{i,2}}{1+\delta} - \lambda_{i,2} = 0, i = 1,2,...,I$

(5c) $\pi_1 - \lambda_{i,1} = 0, i = 1,2,...,I$

(5d) $\frac{\pi_2}{1+\delta} - \lambda_{i,2} = 0, i = 1,2,...,I$

(5e) $R_{i,t} + P_{i,t} - E_{i,t} + A_{i,t} = 0, i = 1,2,...,I$

(5f) $\sum_i P_{i,t} = 0, i = 1,2,...,I; t = 1,2$

Note that, for period 2, the first order conditions are the same as (2). In period 2, the target is fixed, so the problem is identical to (1) and solved as in (3). Substituting this and (5c) in (5a) gives

(5a') $2\alpha_{i,1}R_{i,1} = \pi_1 - \frac{\tau_2\pi_2}{1+\delta}$

Substituting this in (5e), solving for *P* and substituting this in (5f) gives

$$\pi_1 = \frac{\sum_i (E_{i,1} - A_{i,1})}{\sum_i 1/2\alpha_{i,1}} + \frac{\tau_2\pi_2}{1+\delta} \tag{6}$$

Note that solution (6) is identical to (3a) for τ_2=0.

For technology standards (1) changes to:

$$\min_{R_{i1},R_{i2},P_{i1},P_{i2}} C_i = \alpha_{i,1}R_{i,1}^2 + \frac{\alpha_{i,2}R_{i,2}^2}{1+\delta} + \pi_1 P_{\mathrm{i},1} + \frac{\pi_2 P_{\mathrm{i},2}}{1+\delta} \text{ s.t. } R_{i,1} + P_{i,1} \geq E_{i,1} - A_{i,1}; R_{i,2} + P_{i,2} \geq E_{i,2} - A_{i,2} \tag{7}$$

with $\sum_{i=1}^{I} P_{i,t} = 0, t = 1,2$ and $A_{i,2} = \tau_2(E_{i,1} - R_{\max,1} + R_{i,1})$

The first order conditions are (5b-f), while (5a) changes to

(5a'') $2\alpha_{i,1}R_{i,1} = \pi_1 + \frac{\tau_2\pi_2}{1+\delta}$

Equation (6) changes to

$$\pi_1 = \frac{\sum_i (E_{i,1} - A_{i,1})}{\sum_i 1/2\alpha_{i,1}} - \frac{\tau_2\pi_2}{1+\delta} \tag{6'}$$

Again, (6') is identical to (3a) for τ_2=0. The first element of the RHS of (6) and (6') is identical to (3a), so we see that rolling grandfathering (technology standards) increases (decrease) the price of carbon permits. This reflects the fact that there is a penalty (premium) for selling permits.

However, the price increase is exactly compensated by the second element of the RHS of (5a') and (5a''). For every company, emission reduction and therefore net permit trade in period one is unaffected. This is because trade in emission permits is a zero-sum game.

Figure 1 illustrates this. With rolling grandfathering, a company would be prepared to pay more for emission permits, as this would increase its emission allotment in the second period; the demand curve shifts upwards. At the same time, a company would demand a higher price for permits sold, as this would decrease its emission allocation in the second period; the supply curve shifts upwards too. The result is that the same amount is traded in period one, but at a higher price. The reverse happens with technology standards. Both supply and demand curves shift downwards, the quantity traded is the same, but the permit price is lower.

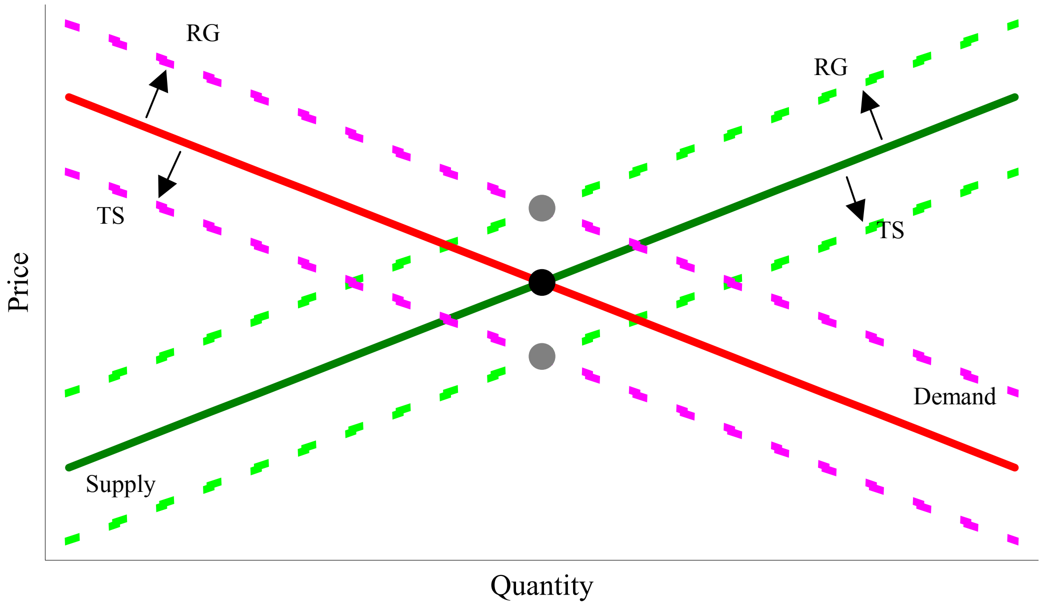

Figure 1. Demand and supply of permits in period 1 for a static allocation (solid lines) and two alternative forms of dynamic allocation, viz. rolling grandfathering (RG) and technology standards (TS).

Something similar happens in the second period. The permit price only depends on the total emission allocation of all companies put together. The emission reductions of each company only depend on the price. So, if rolling grandfathering and technology standards lead to the same total allocation of emission permits, the emission reduction of each company is unaffected. However, as the initial allocation is different, emission permit trade is affected. As a result, the costs of companies are different in both periods, although the total costs are again unaffected. Rolling grandfathering and technology standards have a distributional effect only. This is a reflection of the Coase (1960) Theorem.

3.2 A numerical illustration

The points made above are easily understood with a numerical analysis. Let us assume that there are 5 companies of equal size. Each company emits 20 tC in both period 1 and period 2. In period 1, the emission allocation is 19 tC; in period 2, the emission allocation is 18.50 tC. That is, emission reduction is 5% in the first period and 7.25% in the second (compared to period 0). The firms differ in emission reduction costs. For firm i, $\alpha_{i,1}$=0.01(1+i). In the second period, $\alpha_{i,2}$=0.01i.

Figure 2 shows emission reductions in the first period, without trade and with. The firms are ordered by emission reduction costs. Trade in emission permits makes that firms with low (high) abatement costs do more (less).

Figure 3 shows emission reductions in the second period, without trade and with. Under static allocation, all firms have the same obligations, as they had identical emissions in period 0. Under rolling grandfathering, the firms that bought permits in the first period have a higher allocation (a lower emission reduction obligation). Under a technology standard, the firms that sold permits have a higher allocation. The total emission reduction is the same under the three rules. After trade, emission reduction efforts are the same.

Figure 4 shows the net present value of the emission reduction costs, with a 5% discount rate. Trade reduces the costs for all firms under all three dynamic allocation rules. As expected, companies with very high or low abatement costs benefit most from trade. The net present costs are identical for the three allocation rules.[3] The changes in the permit price in the first period along with the number of traded permits traded in the second period and the emission reduction obligations in the second period offset each other. Compared to a static allocation the permit price in the first period is higher (lower), the total number of traded permits is lower (higher) and the emission reduction obligations for companies with low abatement costs is higher (lower) under rolling grandfathering (technology standard). The intuition behind the fact that net present costs are the same is that the total emission reduction effort is the same, and all companies behave in an optimal way both between the periods and in the market of each period.

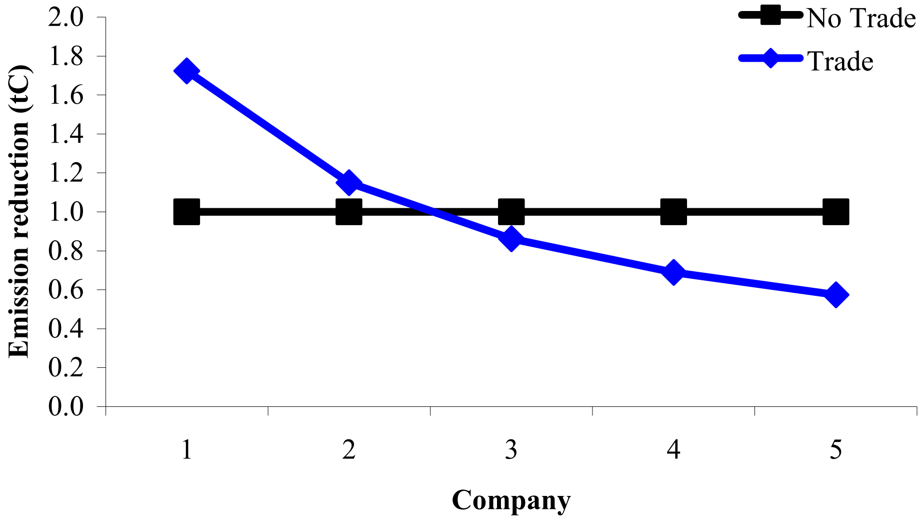

Figure 2. Emission reduction with and without trade in the first period.

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[3] This is a numerical result that is independent of the parameter and target choices. We have not been able to demonstrate this analytically. The problem is that optimal emission reduction in period one depends on the permit prices in both periods, while the permit price in the first period depends on the permit price in the second period, and the permit price in the second period depends on the sum of emission reductions in the first period. In order to make sure that the total emission reduction of the two periods is equal to that of the static allocation, τ_2 also depends on the emission reduction in the first period. Substituting all this in the equation for (say) optimal emission reduction in period 1, a system of simultaneous quadratic equations in R_1 results, with very elaborate constants. There is no general solution to this, and the equations are too complicated to glean insights.

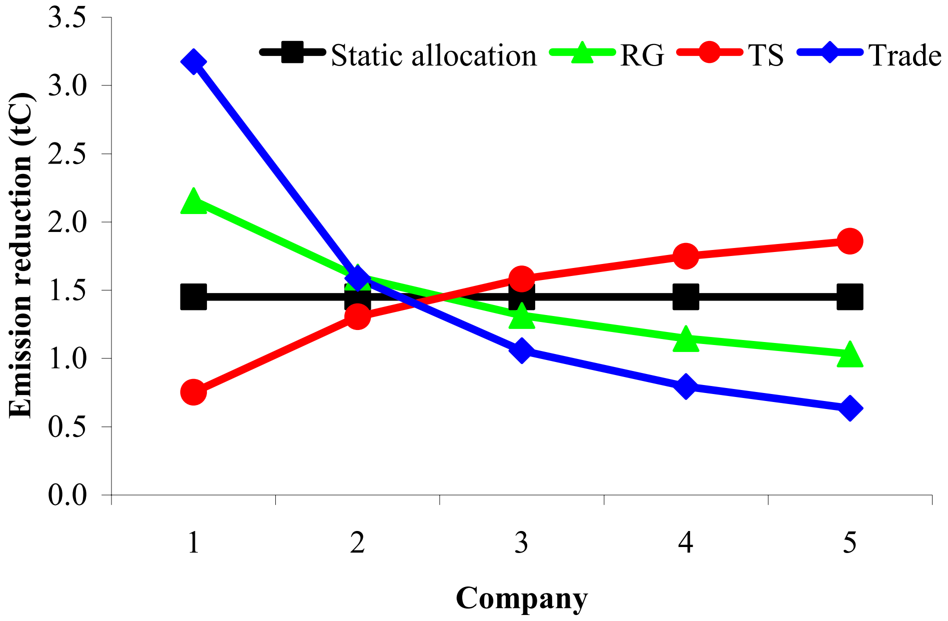

Figure 3. Allocation of emission reduction obligations in the second period according to three alternative rules (static allocation, rolling grandfathering, technology standard), and emission reduction effort after trade.

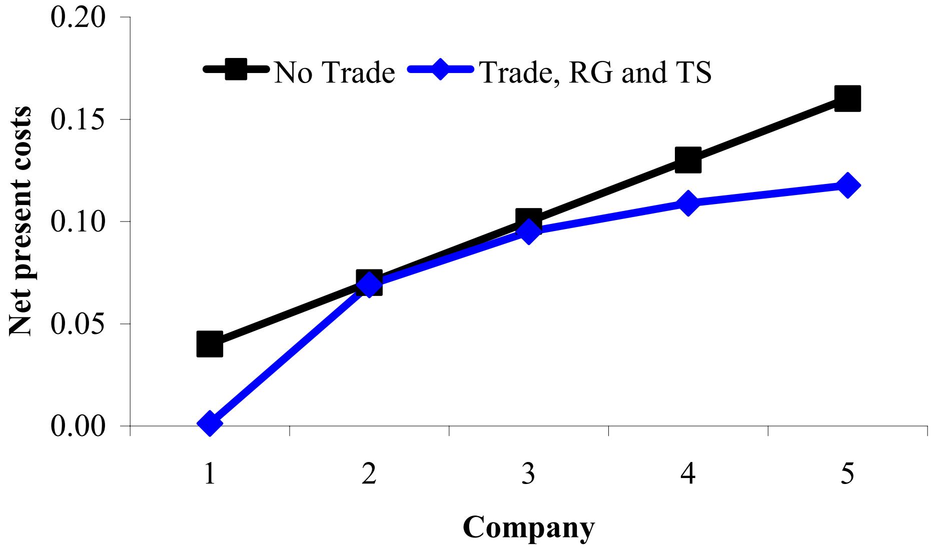

Figure 4. The net present costs of emission reduction without trade and with.

4 Price versus quantity controls

So far, we assumed that the regulator fixes the total amount of emissions in both periods, and we looked at different ways of allocation that to firms. However, it may be that the regulator is rather interested in the costs of emission reduction. This may be because the regulator follows a cost-benefit analysis in setting the emission reduction standard. But even if the regulator has a fixed emission target in mind, uncertainty may lead the regulator to steer on price rather than quantity (Weitzman, 1974; Pizer, 2002). For this reason, many have suggested that a tradable permit system should include a "safety valve" (Pizer, 1999; Jacoby and Ellerman, 2004, McKibben and Wilcoxen, 1997), as indeed the Danish market has (Danish Electricity Supply Act, Act No. 375 of 2 June 1999).

The price observed by the regulator is the permit price. Under rolling grandfathering (a technology standard), the permit price is higher (lower) than the price under static allocation in the first period; the regulator over(under)regulates, and would be induced to release more (less) permits. Comparing (3a) to (6) and solving for the τ in (6) shows how the difference in the amount of permits released:

$$\tau_1{}^* = \tau_1 \pm \frac{\tau_2 \pi_2 \sum_{i=1}^{I} 1/2\alpha_{i,1}}{(1+\delta)\sum_{i=1}^{I} E_{i,0}} \qquad (8)$$

where τ_1 is the original allocation and $\tau_1{}^*$ is the new allocation that assures that the permit price takes the same value as it would have under the static allocation rule. Under rolling grandfathering (technology standard) $\tau_1{}^*$ would be smaller (greater) compared to a static allocation. That is, total emission reduction obligations in period one would be smaller (greater) under rolling grandfathering (technology standard).

Figure 5 illustrates this, using the same numerical model as above. The emission reduction obligations deviate substantially compared to a system of static allocation. Under rolling grandfathering they decrease while they increase for the technology standard. With respect to the net present costs, the effect is stronger for the technology standard than for rolling grandfathering. The reason is that firms under (over) supply the market with permits under rolling grandfathering (technology standards); they are on a steeper (shallower) part of the emission reduction cost function and a small change in the emission reduction obligation has a relatively large (small) effect.

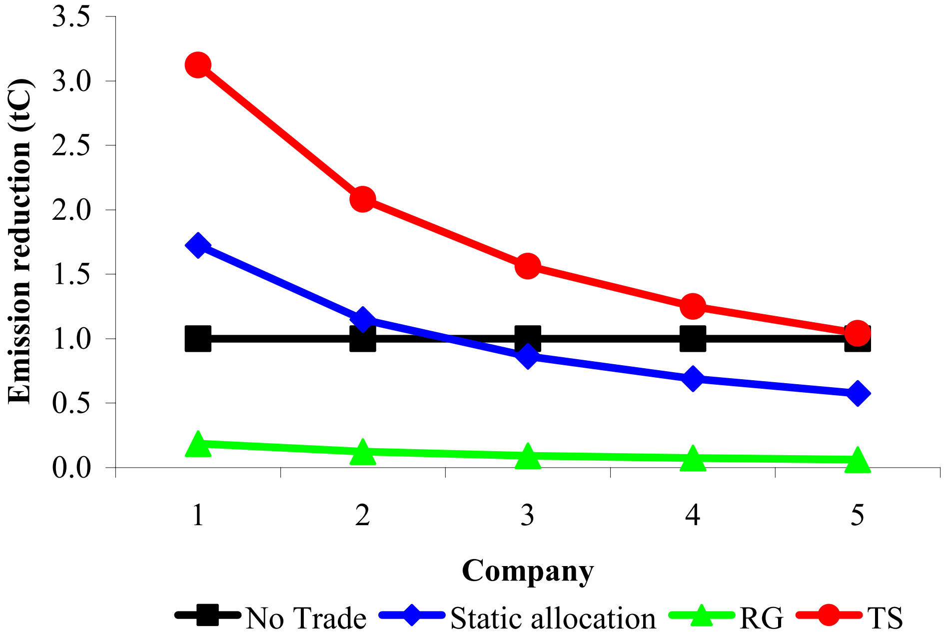

Figure 5. Emission reduction obligation and effort in period 1.

The implications of steering on price rather than quantity are as follows. The more lenient target under rolling grandfathering would primarily benefit the companies with high emission reduction costs, and may hurt the companies with low emission reduction costs. Overall, costs would be lower, though. The stricter target under a technology standard would lead to overall higher costs, but companies with low emission reduction costs may benefit. The broader implication of the above analysis is that, in a *dynamic* permit allocation scheme, the price of permits in any period does not just signal the emission reduction costs in that period, but also incorporates information from later periods. The permit price is therefore harder to interpret and less useful information to policy.

5 Banking and borrowing

Banking and borrowing allow a company to transfer abatement activities over time, forward in time through banking and backward through borrowing. Excess emissions rights can be saved for future use or present emissions can be extended for future abatement. As a result, the permit price becomes arbitraged over time. Whether companies choose to bank or borrow permits depends on the price of the first period compared to a later period. If e.g. the permit price in the first period is expected to be lower compared to the second period, companies would bank permits, increasing the price in the first period and decreasing the price in the second period, until the permit price is balanced over the two periods. This is beneficial to all companies regardless if it is a permit selling or buying company. The cost saving potential is higher for high abatement cost companies compared to the others.

We assume that companies can freely choose to bank or borrow permits, but there is a carbon interest factor $\beta \geq 1$. In a market with permit banking and borrowing equation (1) changes to:

$$(9)\quad \min_{R_{i1},R_{i2},P_{i1},P_{i2},B_{i,1},B_{i,2}} C_i = \alpha_{i,1}R_{i,1}^2 + \frac{\alpha_{i,2}R_{i,2}^2}{1+\delta} + \pi_1 P_{i,1} + \frac{\pi_2 P_{\mathrm{i},2}}{1+\delta} \text{ s.t. } R_{i,1} + P_{i,1} + B_{i,1} \geq E_{i,1} - A_{i,1};$$

$$R_{i,2} + P_{i,2} - \beta B_{i,2} \geq E_{i,2} - A_{i,2}$$

with $\sum_{i=1}^{I} P_{i,t} = 0, t = 1,2$ and $B_{i,1} = B_{i,2}$. $B_{i,1}$ is borrowing; if $B_{i,1}$ is negative it is banking.

First order conditions (10) are (2a), (2b) and (2d), while (2c) changes to

$$(10\text{c})\quad \begin{array}{l} R_{i,1} + P_{i,1} + B_{i,1} - E_{i,1} + A_{i,1} = 0, i = 1,2,...,I; \\ R_{i,2} + P_{i,2} - \beta B_{i,2} - E_{i,2} + A_{i,2} = 0, i = 1,2,...,I \end{array}$$

and

$$(10\text{e})\quad -\lambda_1 + \beta\lambda_2 = 0$$

is added.

(10) solves as (3b), while (3a) changes to:

$$(11\text{a})\quad \pi_1 = \lambda_1 = \frac{\beta\pi_2}{(1+\delta)} = \frac{\sum_{i=1}^{I}(E_{i,1} - A_{i,1})}{\sum_{i=1}^{I} 1/2\alpha_{i,1}} - \frac{\sum_{i=1}^{I} B_{i,1}}{\sum_{i=1}^{I} 1/2\alpha_{i,1}}; \pi_2 = \frac{\lambda_2}{1+\delta} = \frac{\sum_{i=1}^{I}(E_{i,2} - A_{i,2})}{\sum_{i=1}^{I} 1/2\alpha_{i,2}} + \frac{\beta\sum_{i=1}^{I} B_{i,2}}{\sum_{i=1}^{I} 1/2\alpha_{i,2}}$$

At the company level, permits borrowed $B_{i,t}$ and permits bought $P_{i,t}$ are perfect substitutes, and therefore not determined. However, the total amount borrowed is:

$$(11e)\quad \sum_{i=1}^{I} B_{i,1} = \frac{(1+\delta)\sum_{i=1}^{I} {}^{1}\!/_{2\alpha_{i,1}} \sum_{i=1}^{I} {}^{1}\!/_{2\alpha_{i,2}}}{\beta^2 \sum_{i=1}^{I} {}^{1}\!/_{2\alpha_{i,1}} + (1+\delta)\sum_{i=1}^{I} {}^{1}\!/_{2\alpha_{i,2}}} \left[\frac{\sum_{i=1}^{I}(E_{i,1}-A_{i,1})}{\sum_{i=1}^{I} {}^{1}\!/_{2\alpha_{i,1}}} - \frac{\beta}{1+\delta} \frac{\sum_{i=1}^{I}(E_{i,2}-A_{i,2})}{\sum_{i=1}^{I} {}^{1}\!/_{2\alpha_{i,2}}} \right]$$

As expected, Equation (11a) says that if there is net borrowing (banking), the price in the first period is lower (higher), and the price in the second period is higher (lower). (11e) says that there is net borrowing ($\Sigma B_{i,1}>0$) if the emission reduction obligation, normalized by the emission reduction costs, in the first period is large relative to the emission reduction in the second period, corrected for the discount factor and the interest rate on borrowed carbon.

In a system with rolling grandfathering or technology standards the implications are different and depend on the emission reduction obligations in later periods. For rolling grandfathering and intertemporal transfer of permits equation (1) changes to:[4]

$$(12)\quad \min_{R_{i1},R_{i2},P_{i1},P_{i2},B_{i,1},B_{i,2}} C_i = \alpha_{i,1}R_{i,1}^2 + \frac{\alpha_{i,2}R_{i,2}^2}{1+\delta} + \pi_1 P_{i,1} + \frac{\pi_2 P_{i,2}}{1+\delta} \text{ s.t. } R_{i,1} + P_{i,1} + B_i \geq E_{i,1} - A_{i,1};$$
$$R_{i,2} + P_{i,2} - \beta B_i \geq E_{i,2} - A_{i,2}$$

$$\text{with } \sum_{i=1}^{I} P_{i,t} = 0, t = 1,2,\ B_{i,1} = B_{i,2},\ \beta \geq 1 \text{ and } A_{i,2} = \tau_2(E_{i,1} - R_{i,1})$$

Equation (11e) changes to:

$$(13e)\quad \sum_{i=1}^{I} B_{i,1} = \left[\frac{(1+\delta)(1-\frac{\tau_2}{\beta})\sum_{i=1}^{I} {}^{1}\!/_{2\alpha_{i,1}} \sum_{i=1}^{I} {}^{1}\!/_{2\alpha_{i,2}}}{(\beta^2 - 2\beta\tau_2 + \tau_2{}^2)\sum_{i=1}^{I} {}^{1}\!/_{2\alpha_{i,1}} + (1+\delta)\sum_{i=1}^{I} {}^{1}\!/_{2\alpha_{i,2}}} \right]$$
$$* \left[\frac{1}{(1-\frac{\tau_2}{\beta})} \frac{\sum_{i=1}^{I}(E_{i,1}-A_{i,1})}{\sum_{i=1}^{I} {}^{1}\!/_{2\alpha_{i,1}}} - \frac{\beta}{(1+\delta)} \frac{\sum_{i=1}^{I} E_{i,2}}{\sum_{i=1}^{I} {}^{1}\!/_{2\alpha_{i,2}}} + \frac{\beta\tau_2}{(1+\delta)} \frac{\sum_{i=1}^{I} A_{i,1}}{\sum_{i=1}^{I} {}^{1}\!/_{2\alpha_{i,2}}} \right]$$

In contrast to a system of static allocation (11e), Equation (13e) says that there is net borrowing if emission reduction obligations in later periods are large ($0<\tau_2<1$) relative to the first period. Borrowing permits reduces emission reduction obligations in that particular period and increases the number of permits allocated in the next period.

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[4] The first order conditions and the solutions are given in the appendix.

For technology standards and intertemporal transfer of permits equation (1) changes to:[5]

$$(14)\quad \min_{R_{i1},R_{i2},P_{i1},P_{i2},B_{i,1},B_{i,2}} C_i = \alpha_{i,1}R_{i,1}^2 + \frac{\alpha_{i,2}R_{i,2}^2}{1+\delta} + \pi_1 P_{i,1} + \frac{\pi_2 P_{\mathrm{i},2}}{1+\delta} \text{ s.t. } R_{i,1} + P_{i,1} + B_i \geq E_{i,1} - A_{i,1};$$
$$R_{i,2} + P_{i,2} - \beta B_i \geq E_{i,2} - A_{i,2}$$

with $\sum_{i=1}^{I} P_{i,t} = 0, t = 1,2$, $B_{i,1} = B_{i,2}$, $\beta \geq 1$ and $A_{i,2} = \tau_2(E_{i,1} - R_{\max,1} + R_{i,1})$

Equation (11e) changes to:

(13e')

$$\sum_{i=1}^{I} B_{i,1} = \left[\frac{(1+\delta)(1+\frac{\tau_2}{\beta})\sum_{i=1}^{I} 1/2\alpha_{i,1} \sum_{i=1}^{I} 1/2\alpha_{i,2}}{(\beta^2 + 2\beta\tau_2 + \tau_2{}^2)\sum_{i=1}^{I} 1/2\alpha_{i,1} + (1+\delta)\sum_{i=1}^{I} 1/2\alpha_{i,2}} \right]$$
$$* \left[\frac{1}{(1+\frac{\tau_2}{\beta})} \frac{\sum_{i=1}^{I}(E_{i,1} - A_{i,1})}{\sum_{i=1}^{I} 1/2\alpha_{i,1}} - \frac{\beta}{(1+\delta)} \left[\frac{\sum_{i=1}^{I} E_{i,2}}{\sum_{i=1}^{I} 1/2\alpha_{i,2}} + \frac{\tau_2 R_{\max,1}}{\sum_{i=1}^{I} 1/2\alpha_{i,2}} - \frac{\tau_2 \sum_{i=1}^{I} E_{i,1}}{\sum_{i=1}^{I} 1/2\alpha_{i,2}} - \frac{\tau_2 \sum_{i=1}^{I}(E_{i,1} - A_{i,1})}{\sum_{i=1}^{I} 1/2\alpha_{i,2}} \right] \right]$$

Analogous to a system of rolling grandfathering (13e) equation (13e') says that there is net borrowing if emission reduction obligations in later periods are large ($0<\tau_2<1$) relative to the first period. Unlike (13e) the total amount of net borrowed permits is smaller as the emission reduction of the technology leader ($R_{\max,1}$) are subtracted.

Note that, under a dynamic allocation system, intertemporal transfer of permits allows companies to reduce their emission reduction obligations in future periods. The total emission reduction achievement will be lower than the previously defined target. To achieve the same emission reduction target, the regulator has to lower τ_2 and hence increase emission reduction obligations. This has effects on the intertemporal transfer of permits.

Using the numerical example of Section 3.2 and setting τ_2 such that total emission reduction obligations are the same for all approaches the intertemporal transfer of permits under static allocation is almost zero (0.4tC).[6] For rolling grandfathering, borrowing permits is in general more favourable. The total amount of borrowed permits is 4.5tC. This amount is almost identical to the total emissions that have to be reduced (5 tC) in the first period. Under a system of technology standards, banking becomes more favourable. The calculated total amount of banked permits is 1.5tC. In general, net permit borrowing becomes less attractive the lower the regulator sets τ_2 and the more ambitious the emission reduction obligations of future periods are. If τ_2 takes a certain value, net banking becomes more favourable. This is true for all allocation approaches. In our numerical example the regulator has to set τ_2=0.93 for rolling grandfathering and τ_2=0.88 under a technology standard to achieve the same overall emission reductions.

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[5] The first order conditions and the solutions are given in the appendix.

[6] We set β=1.

At the company level the implications might be different. Depending on the dynamic allocation scheme, a companies' abatement costs and the permit price both banking or borrowing might be beneficial. To analyse this at the company level, the dynamic allocation scheme and intertemporal transfer of permits need to be solved simultaneously. This is impossible in our model, as both arbitrage the permit price over time and buying or borrowing permits are perfect substitutes. In the next section, we therefore constrain the amount of intertemporal transferred permits. If the constraint is not binding, there is no solution (see above). We therefore assume that the constraint is binding.

6 Constrained banking and borrowing

We assume that banking and borrowing is restricted to a fraction γ of the emission reduction obligation ($E_{i,t}$-$A_{i,t}$) of the particular period. The company can freely choose to bank permits up to their emission reduction obligations. Borrowing is restricted exogenously by the regulator. The prices of the two periods might not be equalized if the regulator restricts banking or borrowing such that no more permits can be transferred intertemporally in order to comply to the regulator. This would decrease companies' costs less.

In a market with restricted banking and borrowing equation (9) changes to:[7]

$$\text{(9')} \quad \min_{R_{i1},R_{i2},P_{i1},P_{i2},B_{i1},B_{i2}} C_i = \alpha_{i,1}R_{i,1}^2 + \frac{\alpha_{i,2}R_{i,2}^2}{1+\delta} + \pi_1 P_{\mathrm{i},1} + \frac{\pi_2 P_{i,2}}{1+\delta} \quad \text{s.t. } R_{i,1} + P_{i,1} + B_{i,1} \geq E_{i,1} - A_{i,1};$$

$$R_{i,2} + P_{i,2} - \beta B_{i,2} \geq E_{i,2} - A_{i,2}$$

$$\text{with} \quad \sum_{i=1}^{I} P_{i,t} = 0, t = 1,2\,,\ \beta \geq 1, B_{i,1} = B_{i,2}\,, B_{i,1} \leq \gamma(E_{i,1} - A_{i,1}) \text{ and } 0 < \gamma < 1 \text{ for } B_{\mathrm{i},1}>0$$

$$\text{(borrowing)},\ B_{i,1} \geq \gamma(E_{i,1} - A_{i,1}) \text{ and } 0 > \gamma \geq -1 \text{ for } B_{\mathrm{i},1}<0 \text{ (banking)}$$

The results for rolling grandfathering are similar to those obtained in Section 5. If emission reduction obligations in later periods are large ($0<\tau_2<1$) relative to the first period it is rational for all companies to borrow the maximum amount of permits allowed regardless of the permit price in the different periods.

In a system of technology standards with $A_{i,2}$=τ_2($E_{i,1}$- $R_{max,1}$ +$R_{i,1}$) this is only true for companies with high abatement cost. The technology leader and companies with very low abatement costs could reduce their emission reduction obligation only little. Also, they would sell less permits. Those companies might prefer a pure system of banking which would increase the costs for the high cost companies. This is not rational for high abatement cost companies. Therefore, companies with low abatement costs have three different options for minimizing their emission reduction costs. They could bank permits, borrow permits or have no intertemporal transfer of permits.

As companies simultaneously choose the amount of permits to be borrowed, the intertemporal transfer of permits by one company has effects not only on the abatement costs of that company, but via the permit market on that of all other companies. Although borrowing permits might generally be beneficial for all companies, this might no longer be true if all companies would start borrowing permits at the same time. Figure 6 illustrates this by comparing the effects of borrowing permits to a system where no intertemporal transfer is allowed. Displayed are the net present costs using the same numerical example as in Section 3.2. The total emission reduction obligations are the same for all approaches. The net present

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[7] The first order conditions and the solution is given in the appendix. The equations for both dynamic allocation schemes, the first order conditions and the solutions are given in the appendix.

costs for the three different allocation approaches are identical (see Figure 4). Borrowing is restricted to γ=0.5 and identical for all companies, β=1.

Referring to the results obtained in Section 5, Figure 6 shows that borrowing permits is not beneficial for all companies. Companies with high abatement costs would be worse off regardless of the allocation system.[8] A company with low abatement costs would borrow as much as possible as this reduces costs. Under a system of rolling grandfathering, the emission reduction obligations for this company are smaller and it could sell more permits on the market. This reduces costs compared to banking or a system where no intertemporal transfer is allowed. Under a system of technology standards, the same company would have to reduce more emissions relative to a system of no intertemporal transfer. Also, they would sell less permits on the market, but at a higher price. This reduces costs. For a company with high abatement costs (or positive net present costs) limited banking might be beneficial (not displayed here).

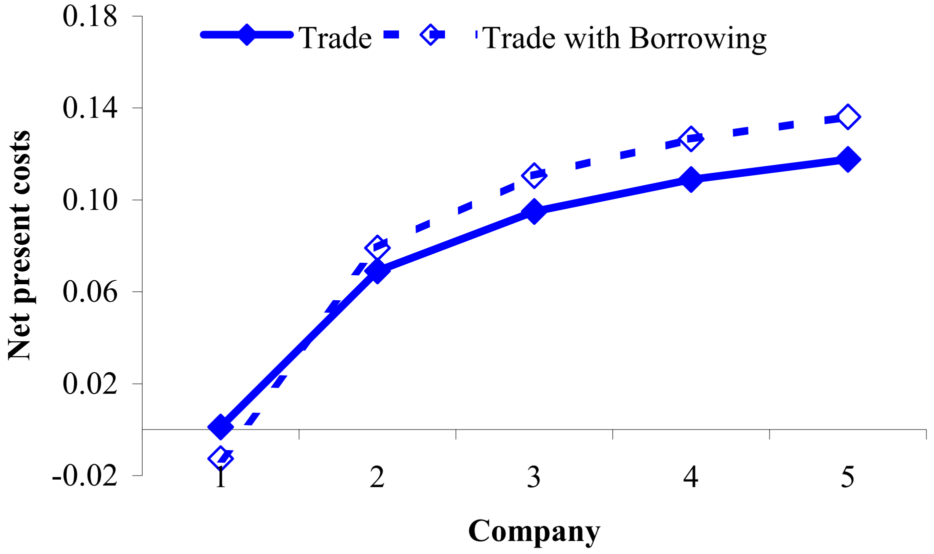

Figure 6. The net present costs of emission reduction with and without intertemporal transfer (γ=0.50). The total emission reduction obligations are the same for all scenarios.

So far, we have assumed that all companies borrow the same percentage of their emission reduction obligations. If companies choose differently between banking and borrowing, the net present costs alter. Figure 7 illustrates this. Both company 1 and 2 borrow permits (γ=0.2) whereas the other companies have no intertemporal transfer (γ=0). Borrowing permits is rational for company 1 and 2 only under rolling grandfathering. They would start banking permits under a technology standard (Figure 7 would be inverted; results not shown).[9] The other companies could bank permits (possible option under rolling gradfathering), borrow permits (possible option under a technology standard). However, their net present costs would

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[8] If $\tau_1 = \tau_2$ (this is all companies have to reduce the same fixed percentage of their emissions of the previous period) it is rational for all companies under rolling grandfathering to borrow the maximum amount of permits allowed regardless of the permit price in the different periods. Under a system of technology standards, the net present cost of the technology leader are always higher compared to a system where banking and borrowing is not allowed. Less permits would be sold at a lower price. This reduces the income from permit trading and reduces costs less. However, banking permits is also not rational for a company with low abatement costs, as it raises the loss from (inter-)national trade further.

[9] The net present costs for companies 1 and 2 would lie in between those obtained for rolling grandfathering and the static allocation.

be lowest, if they would have no intertemporal transfer of permits. The results obtained from our numerical example suggest, that companies selling permits can exert market power and influence other companies emission reduction costs.

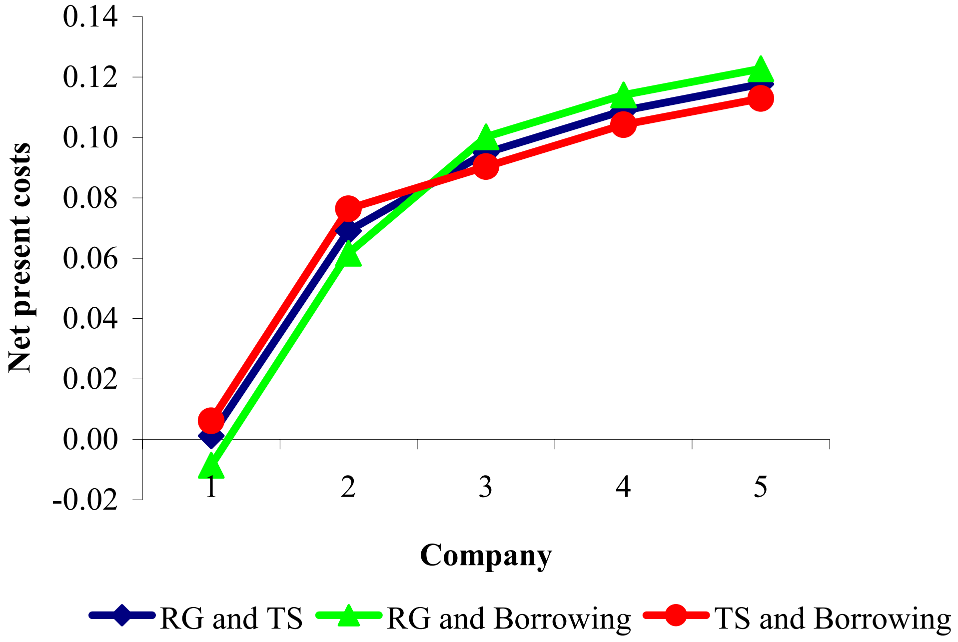

Figure 7. The net present costs of emission reduction with and without intertemporal transfer of permits for the two dynamic allocation schemes. For companies 1 and 2 the intertemporal transfer is restricted to γ=0.2. All other companies have no intertemporal transfer of permits (γ=0).

7 Discussion and conclusion

This paper considers dynamic aspects of allocating greenhouse gas emission permits. We examine three different allocation approaches, one is static while the other two are dynamic. We extend the analysis to investigate two different mechanism to steer overall emission reduction. The regulator can either set the price of emission reduction or set the overall emission reduction target.

We show that different approaches create different strategic incentives at present. With respect to emission reduction efforts rolling grandfathering is best for companies with high abatement costs. Companies with low abatement costs would prefer a technology standard. Also, the two mechanisms to steer overall emission reduction are not equivalent. If the permit price is set such that it takes the same value for all approaches rolling grandfathering becomes the least expensive approach. The reason is that the total emission reduction obligations would be smaller (greater) under rolling grandfathering (technology standard) compared to a static allocation.

Expanding the model to include intertemporal transfer of permits through banking and borrowing the model becomes difficult to handle. The challenge is to solve a system where the permit price becomes arbitraged over time by different factors, the dynamic allocation scheme and the intertemporal transfer of permits. We therefore restrict banking and borrowing. We show that depending on the allocation approach, a companies abatement costs and the emission reduction target banking or borrowing might decrease costs. Intertemporal transfer of permits seems to be benefitial especially for companies with low abatement costs.

The permit sellers on the market. Interestingly, the two dynamic approaches create opposite incentives. The same company would borrow permits under a system of rolling grandfathering and bank permits under a technology standard. As the EU is going to leave it to their member states to decide on how to allocate permits nationally (EU Commission, 2003), this is likely to effect the market not only nationally.

The analysis presented here needs extension in at least two directions. Firstly, emission reduction in period 1 may lead to lower emissions in a later period. This would be the case if investments in emission saving technology have a longer life-time than the policy period. For example, power plants have life-times of 30-50 years, while the UNFCCC commitment periods are 10-15 years. In our model, this implies that the effective emission reduction in period 2 is lower because of emission reduction in period 1. Secondly, more periods than two should be considered. Thirdly, the implementation of banking and borrowing is somewhat unsatisfactory. We are able to derive full results for the corner solution only. Fourthly, the interactions between dynamic target setting and incentives to invest in research and development are ignored. These tasks are deferred to future research.

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APPENDIX

Rolling grandfathering and banking and borrowing

(A1) $\min\limits_{R_{i1},R_{i2},P_{i1},P_{i2},B_{i,1},B_{i,2}} C_i = \alpha_{i,1}R_{i,1}^2 + \frac{\alpha_{i,2}R_{i,2}^2}{1+\delta} + \pi_1 P_{\mathrm{i},1} + \frac{\pi_2 P_{\mathrm{i},2}}{1+\delta}$ s.t. $R_{i,1} + P_{i,1} + B_i \geq E_{i,1} - A_{i,1}$;
$R_{i,2} + P_{i,2} - \beta B_i \geq E_{i,2} - A_{i,2}$

with $\sum_{i=1}^{I} P_{i,t} = 0, t = 1,2$, $\beta \geq 1$, $B_{i,1} = B_{i,2}$ and $A_{i,2} = \tau_2(E_{i,1} - R_{i,1})$

The first order conditions of (A1) are:

(A2a) $2\alpha_{i,1}R_{i,1} - \lambda_{i,1} + \tau_2\lambda_{i,2} = 0, i = 1,2,...,I; \frac{2\alpha_{i,2}R_{i,2}}{1+\delta} - \lambda_{i,2} = 0, i = 1,2,...,I$

(A2b) $\frac{\pi_t}{(1+\delta)^{t-1}} - \lambda_t = 0, i = 1,2,...,I, t = 1,2$

(A2c) $R_{i,1} + P_{i,1} - B_{i,1} - E_{i,1} + A_{i,1} = 0, i = 1,2,...,I; R_{i,2} + P_{i,2} - \beta B_{i,2} - E_{i,2} + A_{i,2} = 0, i = 1,2,...,I$

(A2d) $\sum_{i=1}^{I} P_{i,t} = 0, t = 1,2$

(A2e) $-\lambda_1 + \beta\lambda_2 = 0$

(A2) solves as:

(A3a)

$$\pi_1 = \frac{1}{(1-\frac{\tau_2}{\beta})} \frac{\sum_{i=1}^{I}(E_{i,1} - A_{i,1})}{\sum_{i=1}^{I} {}^{1}\!\big/_{2\alpha_{i,1}}} - \frac{\sum_{i=1}^{I} B_{i,1}}{\sum_{i=1}^{I} {}^{1}\!\big/_{2\alpha_{i,1}}};$$

$$\pi_2 = \frac{\sum_{i=1}^{I} E_{i,2}}{\sum_{i=1}^{I} {}^{1}\!\big/_{2\alpha_{i,2}}} + \frac{\beta\sum_{i=1}^{I} B_{i,2}}{\sum_{i=1}^{I} {}^{1}\!\big/_{2\alpha_{i,2}}} - \frac{\tau_2\sum_{i=1}^{I} B_{i,1}}{\sum_{i=1}^{I} {}^{1}\!\big/_{2\alpha_{i,2}}} - \frac{\tau_2\sum_{i=1}^{I} A_{i,1}}{\sum_{i=1}^{I} {}^{1}\!\big/_{2\alpha_{i,2}}}$$

(A3b) $R_{i,1} = \frac{\pi_1(1-\frac{\tau_2}{\beta})}{2\alpha_{i,1}}; R_{i,2} = \frac{\pi_2}{2\alpha_{i,2}}$

$P_{i,t}$ (A3c) and $B_{i,t}$ (A3d) are not determined.

(A3e)
$$\sum_{i=1}^{I} B_{i,1} = \left[\frac{(1+\delta)(1-\frac{\tau_2}{\beta})\sum_{i=1}^{I} \frac{1}{2\alpha_{i,1}} \sum_{i=1}^{I} \frac{1}{2\alpha_{i,2}}}{(\beta^2 - 2\beta\tau_2 + \tau_2{}^2)\sum_{i=1}^{I} \frac{1}{2\alpha_{i,1}} + (1+\delta)\sum_{i=1}^{I} \frac{1}{2\alpha_{i,2}}} \right] * \left[\frac{1}{(1-\frac{\tau_2}{\beta})} \frac{\sum_{i=1}^{I}(E_{i,1}-A_{i,1})}{\sum_{i=1}^{I} \frac{1}{2\alpha_{i,1}}} - \frac{\beta}{(1+\delta)} \frac{\sum_{i=1}^{I} E_{i,2}}{\sum_{i=1}^{I} \frac{1}{2\alpha_{i,2}}} + \frac{\beta\tau_2}{(1+\delta)} \frac{\sum_{i=1}^{I} A_{i,1}}{\sum_{i=1}^{I} \frac{1}{2\alpha_{i,2}}} \right]$$

Technology standards and banking and borrowing

(A4) $\min_{R_{i1},R_{i2},P_{i1},P_{i2},B_{i,1},B_{i,2}} C_i = \alpha_{i,1}R_{i,1}^2 + \frac{\alpha_{i,2}R_{i,2}^2}{1+\delta} + \pi_1 P_{i,1} + \frac{\pi_2 P_{i,2}}{1+\delta}$ s.t. $R_{i,1} + P_{i,1} + B_i \geq E_{i,1} - A_{i,1}$; $R_{i,2} + P_{i,2} - \beta B_i \geq E_{i,2} - A_{i,2}$

with $\sum_{i=1}^{I} P_{i,t} = 0, t = 1,2$, $\beta \geq 1$, $B_{i,1} = B_{i,2}$ and $A_{i,2} = \tau_2(E_{i,1} - R_{\max,1} + R_{i,1})$

The first order conditions of (A4) are:

(A5a) $2\alpha_{i,1}R_{i,1} - \lambda_{i,1} - \tau_2\lambda_{i,2} = 0, i = 1,2,...,I; \frac{2\alpha_{i,2}R_{i,2}}{1+\delta} - \lambda_{i,2} = 0, i = 1,2,...,I$

(A5b) $\frac{\pi_t}{(1+\delta)^{t-1}} - \lambda_t = 0, i = 1,2,...,I, t = 1,2$

(A5c) $R_{i,1} + P_{i,1} - B_{i,1} - E_{i,1} + A_{i,1} = 0, i = 1,2,...,I; R_{i,2} + P_{i,2} - \beta B_{i,2} - E_{i,2} + A_{i,2} = 0, i = 1,2,...,I$

(A5d) $\sum_{i=1}^{I} P_{i,t} = 0, t = 1,2$

(A5e) $-\lambda_1 + \beta\lambda_2 = 0$

(A5) solves as:

(A6a)
$$\pi_1 = \frac{1}{(1+\frac{\tau_2}{\beta})} \frac{\sum_{i=1}^{I}(E_{i,1}-A_{i,1})}{\sum_{i=1}^{I} \frac{1}{2\alpha_{i,1}}} - \frac{\sum_{i=1}^{I} B_{i,1}}{\sum_{i=1}^{I} \frac{1}{2\alpha_{i,1}}};$$
$$\pi_2 = \frac{\sum_{i=1}^{I} E_{i,2}}{\sum_{i=1}^{I} \frac{1}{2\alpha_{i,2}}} + \frac{\beta\sum_{i=1}^{I} B_{i,2}}{\sum_{i=1}^{I} \frac{1}{2\alpha_{i,2}}} + \frac{\tau_2\sum_{i=1}^{I} B_{i,1}}{\sum_{i=1}^{I} \frac{1}{2\alpha_{i,2}}} + \frac{\tau_2 R_{\max,1}}{\sum_{i=1}^{I} \frac{1}{2\alpha_{i,2}}} - \frac{\tau_2\sum_{i=1}^{I}(E_{i,1}-A_{i,1})}{\sum_{i=1}^{I} \frac{1}{2\alpha_{i,2}}} - \frac{\tau_2\sum_{i=1}^{I} E_{i,1}}{\sum_{i=1}^{I} \frac{1}{2\alpha_{i,2}}}$$

(A6b) $R_{i,1} = \frac{\pi_1(1+\frac{\tau_2}{\beta})}{2\alpha_{i,1}}; R_{i,2} = \frac{\pi_2}{2\alpha_{i,2}}$

$P_{i,t}$ (A6c) and $B_{i,t}$ (A6d) are not determined.

(A6e)

$$\sum_{i=1}^{I} B_{i,1} = \left[\frac{(1+\delta)(1+\frac{\tau_2}{\beta})\sum_{i=1}^{I} {}^{1}\!/\!{}_{2\alpha_{i,1}} \sum_{i=1}^{I} {}^{1}\!/\!{}_{2\alpha_{i,2}}}{(\beta^2 + 2\beta\tau_2 + \tau_2{}^2)\sum_{i=1}^{I} {}^{1}\!/\!{}_{2\alpha_{i,1}} + (1+\delta)\sum_{i=1}^{I} {}^{1}\!/\!{}_{2\alpha_{i,2}}} \right]$$

$$* \left[\frac{1}{(1+\frac{\tau_2}{\beta})} \frac{\sum_{i=1}^{I}(E_{i,1} - A_{i,1})}{\sum_{i=1}^{I} {}^{1}\!/\!{}_{2\alpha_{i,1}}} - \frac{\beta}{(1+\delta)} \left[\frac{\sum_{i=1}^{I} E_{i,2}}{\sum_{i=1}^{I} {}^{1}\!/\!{}_{2\alpha_{i,2}}} + \frac{\tau_2 R_{\max,1}}{\sum_{i=1}^{I} {}^{1}\!/\!{}_{2\alpha_{i,2}}} - \frac{\tau_2 \sum_{i=1}^{I} E_{i,1}}{\sum_{i=1}^{I} {}^{1}\!/\!{}_{2\alpha_{i,2}}} - \frac{\tau_2 \sum_{i=1}^{I}(E_{i,1} - A_{i,1})}{\sum_{i=1}^{I} {}^{1}\!/\!{}_{2\alpha_{i,2}}} \right] \right]$$

Banking and borrowing constrained

(A7) $\min_{R_{i1},R_{i2},P_{i1},P_{i2},B_{i1},B_{i2}} C_i = \alpha_{i,1}R_{i,1}^2 + \frac{\alpha_{i,2}R_{i,2}^2}{1+\delta} + \pi_1 P_{\mathrm{i},1} + \frac{\pi_2 P_{i,2}}{1+\delta}$ s.t. $R_{i,1} + P_{i,1} + B_{i,1} \geq E_{i,1} - A_{i,1}$;
$R_{i,2} + P_{i,2} - \beta B_{i,2} \geq E_{i,2} - A_{i,2}$

with $\sum_{i=1}^{I} P_{i,t} = 0, t = 1,2$, $\beta \geq 1, B_{i,1} = B_{i,2}, B_{i,1} \leq \gamma(E_{i,1} - A_{i,1})$ and $0 < \gamma < 1$ for $B_{\mathrm{i},1}$>0 (borrowing), $B_{i,1} \geq \gamma(E_{i,1} - A_{i,1})$ and $0 > \gamma \geq -1$ for $B_{\mathrm{i},1}$<0 (banking)

The first order conditions of (A7) are:

(A8a) $\frac{2\alpha_{i,t}R_{i,t}}{(1+\delta)^{t-1}} - \lambda_{i,t} = 0, i = 1,2,...,I, t = 1,2$

(A8b) $\frac{\pi_t}{(1+\delta)^{t-1}} - \lambda_t = 0, i = 1,2,...,I, t = 1,2$

(A8c) $R_{i,1} + P_{i,1} - B_{i,1} - E_{i,1} + A_{i,1} = 0, i = 1,2,...,I; R_{i,2} + P_{i,2} - \beta B_{i,2} - E_{i,2} + A_{i,2} = 0, i = 1,2,...,I$

(A8d) $\sum_{i=1}^{I} P_{i,t} = 0, t = 1,2$

(A8e) $-\lambda_1 + \beta\lambda_2 - \lambda_3 = 0$

(A8f) $B_{i,1} - \gamma(E_{i,1} - A_{i,1}) = 0, i = 1,2,...,I$

(A8) solves as:

(A9a) $\pi_1 = \frac{\sum_{i=1}^{I}(E_{i,1} - A_{i,1})}{\sum_{i=1}^{I} {}^{1}\!/\!{}_{2\alpha_{i,1}}} - \frac{\sum_{i=1}^{I} B_{i,1}}{\sum_{i=1}^{I} {}^{1}\!/\!{}_{2\alpha_{i,1}}}; \pi_2 = \frac{\sum_{i=1}^{I}(E_{i,2} - A_{i,2})}{\sum_{i=1}^{I} {}^{1}\!/\!{}_{2\alpha_{i,2}}} + \frac{\beta\sum_{i=1}^{I} B_{i,2}}{\sum_{i=1}^{I} {}^{1}\!/\!{}_{2\alpha_{i,2}}}$

(A9b) $R_{i,t} = \frac{\pi_t}{2\alpha_{i,t}}$

(A9c) $P_{i,1}=\left[(1-\gamma)(E_{i,1}-A_{i,1})\right]-\frac{\pi_1}{2\alpha_{i,1}};P_{i,2}=E_{i,2}-A_{i,2}-\frac{\pi_2}{2\alpha_{i,2}}+\beta\gamma(E_{i,1}-A_{i,1})$

(A9d) $B_{i,1}=\gamma(E_{i,1}-A_{i,1})$

(A9e) $\lambda_3=\frac{\beta}{(1+\delta)}\pi_2-\pi_1$

Rolling grandfathering and banking and borrowing constrained

(A10) $\min\limits_{R_{i1},R_{i2},P_{i1},P_{i2}} C_i=\alpha_{i,1}R_{i,1}^2+\frac{\alpha_{i,2}R_{i,2}^2}{1+\delta}+\pi_1 P_{\mathrm{i},1}+\frac{\pi_2 P_{i,2}}{1+\delta}$ s.t. $R_{i,1}+P_{i,1}+B_{i,1}\geq E_{i,1}-A_{i,1}$;
$R_{i,2}+P_{i,2}-\beta B_{i,2}\geq E_{i,2}-A_{i,2}$

with $\sum_{i=1}^{I}P_{i,t}=0,t=1,2$, $A_{i,2}=\tau_2(E_{i,1}-R_{i,1})$, $\beta\geq 1$, $B_{i,1}\leq\gamma(E_{i,1}-A_{i,1})$, $B_{i,1}=B_{i,2}$ and $0<\gamma<1$ for $B_{\mathrm{i},1}>0$ (borrowing), $B_{i,1}\geq\gamma(E_{i,1}-A_{i,1})$ and $0>\gamma\geq -1$ for $B_{\mathrm{i},1}<0$ (banking)

The first order conditions of (A10) are:

(A11a) $2\alpha_{i,1}R_{i,1}-\lambda_{i,1}+\tau_2\lambda_{i,2}=0,i=1,2,...,I;\frac{2\alpha_{i,2}R_{i,2}}{1+\delta}-\lambda_{i,2}=0,i=1,2,...,I$

(A11b) $\frac{\pi_t}{(1+\delta)^{t-1}}-\lambda_t=0,i=1,2,...,I,t=1,2$

(A11c) $R_{i,1}+P_{i,1}-B_{i,1}-E_{i,1}+A_{i,1}=0,i=1,2,...,I;R_{i,2}+P_{i,2}-\beta B_{i,2}-E_{i,2}+A_{i,2}=0,i=1,2,...,I$

(A11d) $\sum_{i=1}^{I}P_{i,t}=0,t=1,2$

(A11e) $-\lambda_1+\beta\lambda_2-\lambda_3=0$

(A11f) $B_{i,1}-\gamma(E_{i,1}-A_{i,1})=0,i=1,2,...,I$

(A11) solves as:

(A12a)
$$\pi_1=\frac{\sum_{i=1}^{I}(E_{i,1}-A_{i,1})}{\sum_{i=1}^{I}1/2\alpha_{i,1}}-\frac{\sum_{i=1}^{I}B_{i,1}}{\sum_{i=1}^{I}1/2\alpha_{i,1}}+\frac{\tau_2}{1+\delta}\pi_2;$$
$$\pi_2=\frac{\sum_{i=1}^{I}E_{i,2}}{\sum_{i=1}^{I}1/2\alpha_{i,2}}+\frac{\beta\sum_{i=1}^{I}B_{i,2}}{\sum_{i=1}^{I}1/2\alpha_{i,2}}-\frac{\tau_2\sum_{i=1}^{I}B_{i,1}}{\sum_{i=1}^{I}1/2\alpha_{i,2}}-\frac{\tau_2\sum_{i=1}^{I}A_{i,1}}{\sum_{i=1}^{I}1/2\alpha_{i,2}}$$

(A12b) $R_{i,1} = \frac{\pi_1}{2\alpha_{i,1}} - \frac{\tau_2\pi_2}{(1+\delta)2\alpha_{i,1}}; R_{i,2} = \frac{\pi_2}{2\alpha_{i,2}}$

(A12c) $P_{i,1} = \left[(1-\gamma)(E_{i,1}-A_{i,1})\right] - \frac{\pi_1}{2\alpha_{i,1}} + \frac{\tau_2\pi_2}{(1+d)2\alpha_{i,1}}; P_{i,2} = E_{i,2} - A_{i,2} - \frac{\pi_2}{2\alpha_{i,2}} + \beta\gamma(E_{i,1}-A_{i,1})$

(A12d) $B_{i,1} = \gamma(E_{i,1}-A_{i,1})$

(A12e) $\lambda_3 = \frac{\beta}{(1+\delta)}\pi_2 - \pi_1$

Technology standard and banking and borrowing constrained

(A13) $\min_{R_{i1},R_{i2},P_{i1},P_{i2}} C_i = \alpha_{i,1}R_{i,1}^2 + \frac{\alpha_{i,2}R_{i,2}^2}{1+\delta} + \pi_1 P_{i,1} + \frac{\pi_2 P_{i,2}}{1+\delta}$ s.t. $R_{i,1} + P_{i,1} + B_{i,1} \geq E_{i,1} - A_{i,1}$;
$R_{i,2} + P_{i,2} - \beta B_{i,2} \geq E_{i,2} - A_{i,2}$

with $\sum_{i=1}^{I} P_{i,t} = 0, t = 1,2$, $A_{i,2} = \tau_2(E_{i,1} - R_{\max,1} + R_{i,1})$, $\beta \geq 1$, $B_{i,1} \leq \gamma(E_{i,1}-A_{i,1})$, $B_{i,1} = B_{i,2}$ and $0 < \gamma < 1$ for $B_{i,1}>0$ (borrowing), $B_{i,1} \geq \gamma(E_{i,1}-A_{i,1})$ and $0 > \gamma \geq -1$ for $B_{i,1}<0$ (banking)

The first order conditions of (A13) are:

(A14a) $2\alpha_{i,1}R_{i,1} - \lambda_{i,1} - \tau_2\lambda_{i,2} = 0, i = 1,2,...,I; \frac{2\alpha_{i,2}R_{i,2}}{1+\delta} - \lambda_{i,2} = 0, i = 1,2,...,I$

(A14b) $\frac{\pi_t}{(1+\delta)^{t-1}} - \lambda_t = 0, i = 1,2,...,I, t = 1,2$

(A14c) $R_{i,1} + P_{i,1} - B_{i,1} - E_{i,1} + A_{i,1} = 0, i = 1,2,...,I; R_{i,2} + P_{i,2} - \beta B_{i,2} - E_{i,2} + A_{i,2} = 0, i = 1,2,...,I$

(A14d) $\sum_{i=1}^{I} P_{i,t} = 0, t = 1,2$

(A14e) $-\lambda_1 + \beta\lambda_2 - \lambda_3 = 0$

(A14f) $B_{i,1} - \gamma(E_{i,1}-A_{i,1}) = 0, i = 1,2,...,I$

(A14) solves as:

(A15a)
$$\pi_1 = \frac{\sum_{i=1}^{I}(E_{i,1}-A_{i,1})}{\sum_{i=1}^{I} 1/2\alpha_{i,1}} - \frac{\sum_{i=1}^{I} B_{i,1}}{\sum_{i=1}^{I} 1/2\alpha_{i,1}} - \frac{\tau_2}{1+\delta}\pi_2;$$
$$\pi_2 = \frac{\sum_{i=1}^{I} E_{i,2}}{\sum_{i=1}^{I} 1/2\alpha_{i,2}} + \frac{\beta\sum_{i=1}^{I} B_{i,2}}{\sum_{i=1}^{I} 1/2\alpha_{i,2}} + \frac{\tau_2\sum_{i=1}^{I} B_{i,1}}{\sum_{i=1}^{I} 1/2\alpha_{i,2}} + \frac{\tau_2 R_{\max,1}}{\sum_{i=1}^{I} 1/2\alpha_{i,2}} - \frac{\tau_2\sum_{i=1}^{I}(E_{i,1}-A_{i,1})}{\sum_{i=1}^{I} 1/2\alpha_{i,2}} - \frac{\tau_2\sum_{i=1}^{I} E_{i,1}}{\sum_{i=1}^{I} 1/2\alpha_{i,2}}$$

(A15b) $R_{i,1} = \frac{\pi_1}{2\alpha_{i,1}} + \frac{\tau_2\pi_2}{(1+\delta)2\alpha_{i,1}}; R_{i,2} = \frac{\pi_2}{2\alpha_{i,2}}$

(A15c) $P_{i,1} = \left[(1-\gamma)(E_{i,1} - A_{i,1})\right] - \frac{\pi_1}{2\alpha_{i,1}} - \frac{\tau_2\pi_2}{(1+d)2\alpha_{i,1}}; P_{i,2} = E_{i,2} - A_{i,2} - \frac{\pi_2}{2\alpha_{i,2}} + \beta\gamma(E_{i,1} - A_{i,1})$

(A15d) $B_{i,1} = \gamma(E_{i,1} - A_{i,1})$

(A15e) $\lambda_3 = \frac{\beta}{(1+\delta)}\pi_2 - \pi_1$

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