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DISCUSSION PAPER

Implications of Linking National Emission Trading Schemes prior to the Start of the First Commitment Period of the Kyoto Protocol

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ABSTRACT

After greenhouse gas emission trading on country level had been proposed by the Kyoto Protocol agreed on in 1997, a discussion on the introduction of national schemes with entities as participants ensued. This discussion also raised the question if and how such systems can be linked. We first discuss this issue with regard to technical feasibility and environmental integrity. We find that linking is generally not prevented due to technical reasons. Environmental integrity may, however, be endangered depending on the specific designs of the schemes to be linked. We then analyse the economic impact of linking national schemes. Even though linking national schemes can increase overall cost-efficiency this picture changes if systems are linked prior to the start of the first Kyoto commitment period. Seller and buyer may have different interests with regard to linkage and the transfer of AAUs (= emission rights under the Protocol). Voluntarily linking can thus not be expected. In case that the linkage is prescribed by super-national organisations as for example the EU commission, both winners and losers are likely to be produced. This in turn may refrain member states from approving such approaches.

JEL-Classification: Q25, Q28

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1 Introduction

Emission trading was first introduced in the US during the mid 1970s. It was applied in several ways (e.g. lead-free petrol, ozone depleting chemicals) among which the acid rain programme may have the closest similarity with potential national CO_2 trading schemes (UN 1995 pp. 19-23). In the context of the UN Framework Convention on Climate Change it first seemed that national taxes could be the instruments of choice for countries to control the GHG emissions (NRP 1995 p.1). However, emission trading on country level was finally formally introduced with the Kyoto-Protocol agreed on in 1997. As Parties to the Protocol do, however, lack information on abatement options and costs the theoretical efficiency gains may never be realised by nation to nation trading. This might be one reason why the discussion on national trading schemes, i.e. involving sub-national entities, has remarkably intensified since then: Numerous reports by “industry/governmental” working groups have been published throughout the industrialised world. With national schemes emerging, the question of linkage evolves. We analyse this aspect for technical feasibility, environmental integrity and economic impacts. The latter aspect will be investigated focussing on the interaction of linking national schemes in the context of the Kyoto-provisions only: There is a general agreement that the linking of different schemes itself increases overall cost-efficiency.

2 Emission trading

2.1 The concept of emission trading

Compared to other economic instruments like taxation, emission trading has the advantage that the total quantity of emissions can be determined prior to the introduction of the instrument by the quantity of emission rights/permits issued by authorities. (In the following the terms *emission right* and *permit* are used equivalently). Furthermore, emission trading allows for a cost efficient meeting of emission targets as long as the market functioning is assured. Initially, each participant has to be assigned a certain number of emission rights. At the end of the period every participant must hold at least a quantity of emission rights equivalent to the emissions released into the atmosphere. Any surplus permits can be sold on the market (or possibly be banked). Buyers are those emitters whose marginal abatement costs are higher than the permit price on the market. In the long run abatement costs are to be equal.

However, before national schemes can start operation in real economies, several design features need to be decided on.

2.2 Design of national ET-schemes

When implementing national trading schemes, many characteristics affecting economic efficiency, environmental integrity and acceptability[1] have to be taken into consideration (see for example AGE (2002), AGO (1999), CCAP (1999) , Haites, E, Aslam, M. E. (2000), IEA (1999), Kerr (1998), MIES (2000), NZME (1998))

Even though there is an intensive discussion on the implementation of GHG emission trading schemes on entity level, only two public[2] systems currently exist in Europe: in Denmark and the United Kingdom.[3]

3 Linking schemes

As long as the abatement costs in separate trading schemes are different, the linkage of two schemes can result in increased overall cost-efficiency. However, given that on the balance one country is either a net importer or a net exporter, the permit price will go down in the former and go up in the latter. Consequently, selling entities in the importing countries will loose whereas buyers will win. The contrary applies for the exporting country. This in turn may prompt the loosing participants to turn down the linking to schemes in advance (Haites & Mullins 2001 p. viii).

Different approaches in designing national schemes generally lead to different effects with regard to the criteria mentioned above. They are, however, a general concern in the design of a national system. Differences may either prevent linkage for technical reasons or effect environmental integrity when schemes are linked. Table 1 shows in which way these two points are affected.

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1 Including compatibility with existing regulation, equity and competitiveness issues.

2 Private systems exist within the companies BP and Shell.

3 The Dutch Erupt/Cerupt programme (see: www.carboncredits.nl) and the Hamburg CO_2 competition (see: www.hwwa.de/Projects/Res_Programmes/RP/Klimapolitik/CO2%20competition.htm) cannot be considered as a trading scheme on entity level even though they have been successfully implemented with business being involved.

Table 1
Linking national trading schemes:
Technical feasibility and environmental integrity

Design feature	Effect of differences in design features
Absolute vs. Specific Target	Linkage technically feasible as long as some units are defined (e.g. t CO2) but risk of weakening env integrity in case permits are sold on the balance from the specific to the absolute system by increasing output (see also AGE 2002b p. 34)
Stringency of target	Linkage technically feasible; overall stringency remains unaffected from linking (for different incentives to manipulate stringency prior to the linkage see discussions in section on economic compatibility).
Mandatory vs. Voluntary participation	Linkage technically feasible; as permit price will go up in one system and go down in the other one, incentives to join may also be increased. In case that allocation of permits is generous ("hot air") in the system where prices go up, a greater number may volunteer due to linkage and thus env. Integrity can be weakened.
Participants	Linkage technically feasible; env. integrity may be endangered especially if systems with direct and indirect emissions from the same product are linked
Coverage of gases	Technical feasibility and environmental integrity are unproblematic with regard to linking schemes with different coverage of gases as long as reasonable conversion factors are applied in both systems.*)
Mode of allocation	The method of allocation is not affecting technical feasibility of linkage nor env. integrity
Monitoring, Verification and Reporting (MVR)	Technical feasibility unaffected from MVR; higher prices due to linking and lax MVR provisions may give incentives to cheat and thus affect env. integrity
Banking and borrowing	No impact on technical feasibility or env. integrity for banking. For borrowing difference do not cause technical problems but can undermine env. intergrity
Non-compliance provisions	Linkage technically feasible; but difference in penalties and enforcement can weaken env. effectiveness as the lowest penalty determines the place of non-compliance.
Market access	Unproblematic from both technical and environmental point of view.
Register	Can a priori prevent linkage as well as negatively affect env. integrity. However, structures can be adopted causing higher costs.
Use of project based credits	Linkage technical feasible; env. integrity might be affected if quality of standards is different.
Treatment of new sources / plant shut down	Technically unproblematic; env. integrity may be affected in case perverse incentives to create new source due to generous allocation are given.
Compliance period	Unproblematic from both technical and environmental point of view.
Liability	With different liability provisions, trading would have to be limited to surplus permits on the sellers account after compliance has be established.

*) Global Warming Potentials (GWP) adopted in the Kyoto-Protocol have been adopted by a political decision. Other conversion factors for different gases are also conceivable (see for example IPCC (2001) pp. 388-390).

Argumentation following Haites & Mullins (2001 pp. 38-64)

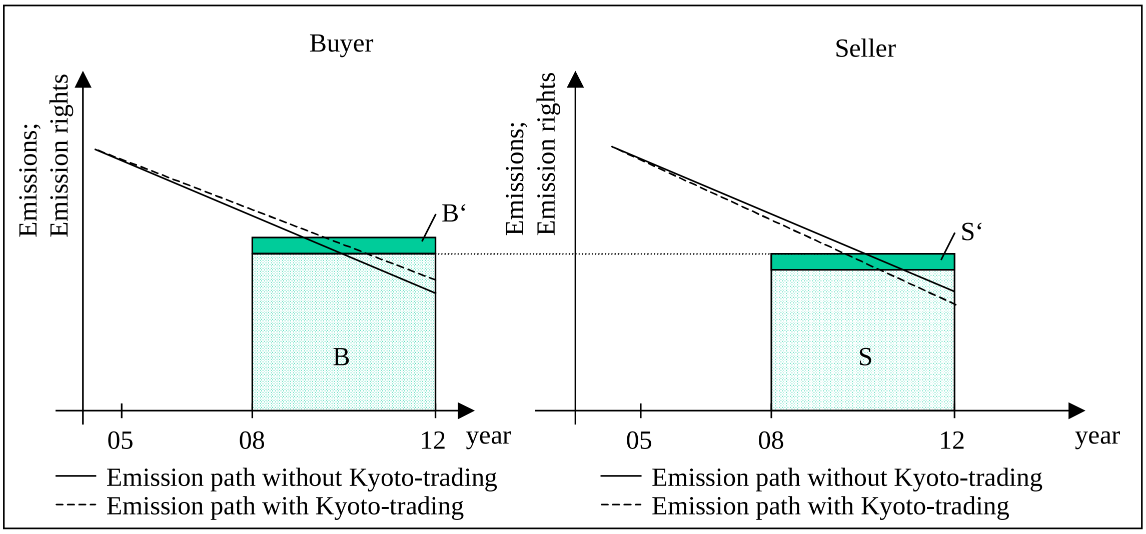
4 Linking national schemes in the context of the Kyoto-Protocol

After having discussed the linkage of national schemes from a technical and an environmental perspective, we analyse in following section the economic impact in the context of the Kyoto-provisions.

4.1 The Kyoto-Provisions

The Kyoto-Protocol – agreed on during the 3rd Conference of Parties to the UNFCCC in Kyoto in 1997 - defines absolute emission targets (so-called Assigned Amount) for countries listed in Annex B for the first commitment period from 2008-2012. The targets are defined as a percentage figure compared to 1990's GHG emissions. In order to enable a cost-efficient meeting of these targets some so-called flexible mechanisms have been introduced, among which emission trading: Parties listed in Annex B to the Protocol are under certain conditions allowed to trade the underlying emission rights, the so-called Assigned Amount Units (AAUs). Emissions without any flexible mechanisms would have to decline sooner or later in all countries according to the national targets. With trading, the emission path will change – maybe even before 2008[1] (see Fig. 2).

Figure 1
Change of emission path considering emissions trading under the Kyoto provisions for a simple 2 country case



1 The Netherlands represent a good example. Since they acknowledged that meeting the Kyoto target at home would be quite expensive, they prepared the purchase of emission rights under the Kyoto-provisions. This allows for increased emissions according to the no-Kyoto-trading case even before 2008 (see www.carbencredits.nl for further information).

However, as the system starts in 2008 only, one has to ask how international pre-2008 trading interacts with the Kyoto provisions.

It is interesting to note that there are no concrete mandatory emissions paths for reaching the Kyoto-targets: Article 3 (2) of the Kyoto-Protocol says that "Each Party included in Annex I shall, by 2005, have made demonstrable progress in achieving its commitments under this Protocol" but it will be interesting to see how the term *demonstrable progress* will be interpreted in 2005. As there is furthermore no penalty mentioned in case a Party does not show any demonstrable progress, the emission path can be assumed to be completely undetermined.

4.2 International trading prior to the first commitment period

The intuitive approach for international emissions trading prior 2008 might be the mutual acceptance of the national "currencies". We refer to these as *pre-Kyoto units* (PKUs). As mentioned above, linking trading schemes can result in increased overall cost-efficiency on the international scale. However, apart from efficiency on a global scale, the incidence of costs has to be discussed. Keeping the latter aspect in mind, a government may be reluctant to link schemes as the PKUs purchased would be "worthless" with regard to the Kyoto-target at the end of 2007. A similar situation can currently be observed in The Netherlands: The Dutch government had introduced tax reductions for green electricity. As national capacities were to small to satisfy demand, green energy was imported. As the Dutch government realised that this was not helpful with regard to an remarkable increase of domestic production of green energy, it chose to stop the tax reductions (Anonymous 2002).

Thus, potential buyers may either reject early linkage or insist on the exchange of AAUs along with PKUs. This latter point becomes more obvious as investments in CDM-projects prior to 2008 offer another source for cheap reductions and as generated CERs are eligible for the Kyoto target in the first commitment period (see Fig. 3) Again the Dutch activities within the CERUPT programme (Senter (2002)) may serve as example.

With regard to the CERs generated before 2008 one has to discuss how the are delt with. They could generally be used two times. First, within the national trading scheme prior to the first commitment period where they would be withdrawn by national authorities without becoming invalid with regard to the obligations under the Protocol. Second within the Kyoto scheme starting 2008.

For analysing the different schemes we consider a two country, two period model and analyse at first the situation without any international trading prior to the first commitment period.

4.2.1 *Kyoto-trading only*

We assume that – with regard to the Kyoto target – one country will be a net buyer whereas the other will be a net seller. (Note that the model discussed below has been rigidly simplified for illustrative purposes. A general version is presented in Annex 1.) Both countries have the same reduction obligation in each period (that changes, however, over time). Banking is not allowed. The cost functions for the two schemes are quadratic. (They are the aggregated abatement cost functions of the participants in the two schemes.

We follow two different approaches with regard to the abatement options. In the first one the lifetime of an investment in emission reductions is one period. In the second it lasts for both periods without inducing costs in second period. The second approach has been put in the Annex 6 to remain clarity. Both approaches will, however, be discussed together at the end.

Without loss of generality, let *a* denote the buying and *b* the selling country. Indices 1 and 2 denote the two periods. The two countries face the optimisation problem:

(1)

$$\min_{R_{a1},R_{a2},P_2} C_a = \alpha_a R_{a1}^2 + \alpha_a R_{a2}^2 + \pi_2 P_2 \; ; \quad \min_{R_{b1},R_{b2},P_2} C_b = \alpha_b R_{b1}^2 + \alpha_b R_{b2}^2 - \pi_2 P_2$$

s.t.

$$R_{a1} \geq T_1 \; ; \quad R_{b1} \geq T_1 \; ; \quad R_{a2} + P_2 \geq T_2 \; ; \quad R_{b2} - P_2 \geq T_2$$

where, C = Costs, α = parameter, R = emissions reduced internally, π = permit price (assuming a perfect market where each participants faces the same price), P = quantity of permits bought or sold, T = reduction obligation

Whereas T_2 should be based on the Kyoto-target there is more freedom when defining T_1 (see next chapter for a more detailed discussion).

First order conditions are given in Annex 2. (1) solves as:

(2)

$$R_{a1} = T_1 \;;\; R_{b1} = T_1 \;;\; \lambda_{a1} = 2a_a T_1 \;;\; \lambda_{b1} = 2a_b T_1$$

$$R_{a2} = \frac{2\alpha_b}{\alpha_a + \alpha_b} T_2 \;;\; R_{b2} = \frac{2\alpha_a}{\alpha_a + \alpha_b} T_2 \;;\; \pi_2 = \lambda_{a2} = \lambda_{b2} = \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} T_2 \;;\; P_2 = \frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_2$$

where λ = Lagrange multiplier

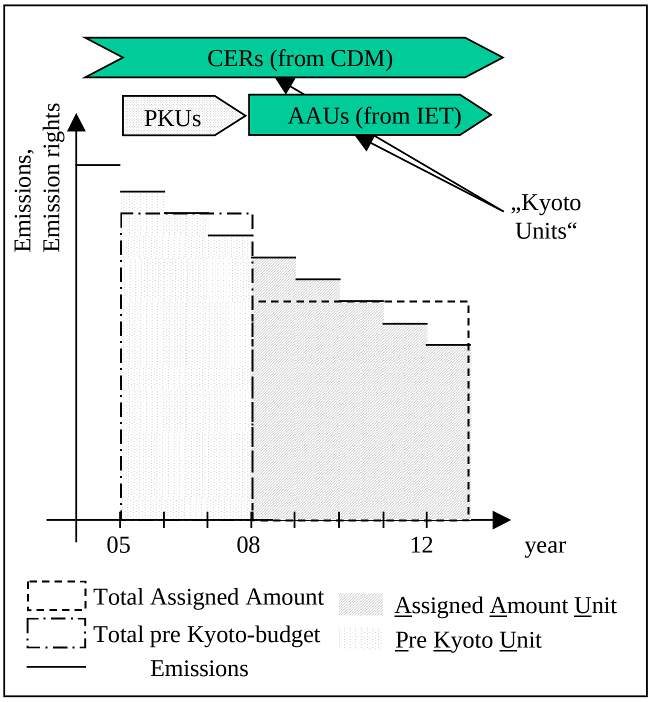
We can see, that by introducing trading in the second period, marginal abatement costs (λ_{i2}) become the same for both countries.

4.2.2 *Non AAU-based international emission trading before 2008*

In case that no AAUs are used in the linked schemes another "commodity"[1] has to be transferred. Let us denote the commodity as *Pre-Kyoto-Unit (PKU)* as mentioned above. Generally, a government can issue as much as PKUs as desired. The selling country actually has an incentive to increase the number of permits as it is beneficial to its industry. Since this is at the expense of the environment, a pro-environmental buying country may look for instruments to reduce import of "worthless" permits. Rehdanz and Tol (2002) analyse the different impacts of a discount factor, a tariff and a quantity limit. In the following analysis we assume, however, that the PKU allocation prior to the first commitment period is based on the Assigned Amount and that arbitrarily flooding of the market does not occur. For a linear compliance path the situation can be as depicted in Figure 2:

1 It is still not clear what legal status the permits will have (commodity, commercial paper etc.).

Figure 2
Permit budget prior and during the first commitment period



Extending (1) with trading in both periods gives:

(3)

$$\min_{R_{a1},R_{a2},P_1,P_2} C_a = \alpha_a R_{a1}^2 + \pi_1 P_1 + \alpha_a R_{a2}^2 + \pi_2 P_2 \; ; \quad \min_{R_{b1},R_{b2},P_1,P_2} C_b = \alpha_b R_{b1}^2 - \pi_1 P_1 + \alpha_b R_{b2}^2 - \pi_2 P_2$$

s.t.

$$R_{a1} + P_1 \geq T_1 \; ; \quad R_{b1} - P_1 \geq T_1 \; ; \quad R_{a2} + P_2 \geq T_2 \; ; \quad R_{b2} - P_2 \geq T_2$$

First order conditions are given in annex 3. (3) solves as:

(4)

$$R_{a1} = \frac{2\alpha_b}{\alpha_a + \alpha_b} T_1 \; ; \quad R_{b1} = \frac{2\alpha_a}{\alpha_a + \alpha_b} T_1 \; ; \quad \pi_1 = \lambda_{a1} = \lambda_{b1} = \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} T_1 \; ; \quad P_1 = \frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_1$$

$$R_{a2} = \frac{2\alpha_b}{\alpha_a + \alpha_b} T_2 \; ; \quad R_{b2} = \frac{2\alpha_a}{\alpha_a + \alpha_b} T_2 \; ; \quad \pi_2 = \lambda_{a2} = \lambda_{b2} = \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} T_2 \; ; \quad P_2 = \frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_2$$

where λ = Lagrange multiplier

It is striking that the result is completely symmetric. This is simply because the schemes in the two periods are not linked and we thus have to separate the systems. (PKUs traded in the first period do not occur after this period has be ended.) Remember that discounting has been neglected for simplicity reasons.

As we can furthermore see, the quantity of PKU purchased by country *a* depends on the reduction obligation and the abatements costs in the two countries. Even though being in compliance with the pre Kyoto-target, emissions are less reduced in the buying country in the pre-Kyoto period than without any linkage of the trading schemes. As permits are bought, country *a* ultimately finances the emission reductions in country *b* without getting anything in return. It could not even state that it has made *demonstrable progress in emission reductions.* Consequently, government *a* may argue for weak reduction obligations in the pre-Kyoto period or insist on a transfer of AAU in order to benefit in some way. This point is analysed in the next section. Note, however, that this system would be cost-efficient from a global climate policy perspective.

4.2.3 *AAU-based international emission trading before 2008*

We still assume, that the national total budgets are consistent with the Kyoto target.

As a consequence of the aforementioned "subsidy effect" we now assume that the buying country demands a transfer of an equal quantity of AAUs with each PKU bought from the other country. As emissions must only be "backed-up" by AAUs from 2008 on, they can be used for any trading scheme prior to the start of the Kyoto scheme. They do not have to be redeemed, let us say at the end of 2007. Thus, the total quantity of AAUs will not change due to their use in early trading schemes. However, ownership will change.

We consider the aforementioned by changing the budget constraint in (2). Any permit bought (sold) in period 1 is added (subtracted) in the second period. (Note that this is no banking in the traditional sense):

(5) $R_{a1} + P_1 \geq T_1$; $R_{b1} - P_1 \geq T_1$; $R_{a2} + P_2 + P_1 \geq T_2$; $R_{b2} - P_2 - P_1 \geq T_2$

See annex 4 for first order conditions. (5) solves as:

(6)

$$R_{a1} = \frac{2\alpha_b}{\alpha_a + \alpha_b} T_1 \;;\; R_{b1} = \frac{2\alpha_a}{\alpha_a + \alpha_b} T_1 \;;\; \pi_1 = \lambda_{a1} = \lambda_{b1} = \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} T_1 \;;\; P_1 = \frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_1$$

$$R_{a2} = \frac{2\alpha_b}{\alpha_a + \alpha_b} T_2 \;;\; R_{b2} = \frac{2\alpha_a}{\alpha_a + \alpha_b} T_2 \;;\; \pi_2 = \lambda_{a2} = \lambda_{b2} = \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} T_2 \;;$$

$$P_2 = \frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_2 + \frac{(\alpha_b - \alpha_a)}{\alpha_a + \alpha_b} T_1$$

Comparing (6) with (4) we can see that the quantity traded in period 2 (P_2) changes. As definition $\alpha_b - \alpha_a < 0$ by (a is the buying country) the second addend becomes negative and thus less permits are traded. Thus, with all other unknowns being unchanged, the transfer of AAUs along with PKUs reduces the total costs in the buying country (see next chapter for detailed discussion). The latter should argue for strong reduction obligations in the pre-Kyoto period (second addend for P_2 in (6)) . On the other hand, total costs are increasing for the selling country which in turn should prefer the approach presented first (no-AAU-transfer).

4.3 Discussion and Conclusion

If we take the results in (2), (4) and (6) and substitute them in the cost functions we get the compliance costs for both countries (see annex 5 and 7; equations for the long living investments approach are marked by "*").

<u>Investment lifetime one period:</u>

We find that the buying country prefers the AAU-transfer to the no-AAU-transfer scenario. It prefers, however, both approaches to the "Kyoto-trading only" case as long as we assume that the government is interested in cost-efficient international climate policy instruments prior to the start of the first commitment period. It may, however, be reluctant to "subsidise" reductions in other countries without getting anything in return.

The situation is, however, different for the selling country: It prefers the no-AAU-transfer scenario to all other options. Furthermore, it favours the Kyoto-only approach over the AAU-transfer one because additional costs from foregoing benefits from trading in the first period are overcompensated by reduced costs in the second period (see Annex 5).

Apart from this, both countries do have different interests with regard to the stringency of the reduction obligation in period 1 (see Table 2).

Investment lifetime two periods:

As for the "one period lifetime" approach, the net buying countries prefers the AAU-transfer to all other schemes as costs are lowest. However, the situation has changed with regard to the comparison between the Kyoto-trading-only and the no-AAU-transfer case: Due to the "unlimited" lifetime of investments in abatement options, costs are lower in the second period when emissions are reduced "at home" during the first period.

Expenses for buying permits in the second period amount to

Kyoto-Trading only:

$$C_{a_2}^{(1)*} = \frac{4\alpha_a\alpha_b}{\alpha_a + \alpha_b}(T_2 - T_1)\left[\frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b}T_2 + \frac{(\alpha_b - \alpha_a)}{\alpha_a + \alpha_b}T_1\right]$$

No-AAU-transfer:

$$C_{a_2}^{(2)*} = \frac{4\alpha_a\alpha_b}{\alpha_a + \alpha_b}(T_2 - T_1)\frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b}T_2 .$$

Thus, costs in the second period are reduced in the Kyoto-trading-only case compared to no-AAU-transfer case by $\Delta C_{a_2}^{*} = \frac{4\alpha_a\alpha_b}{\alpha_a + \alpha_b}(T_2 - T_1)\frac{(\alpha_b - \alpha_a)}{\alpha_a + \alpha_b}T_1$.

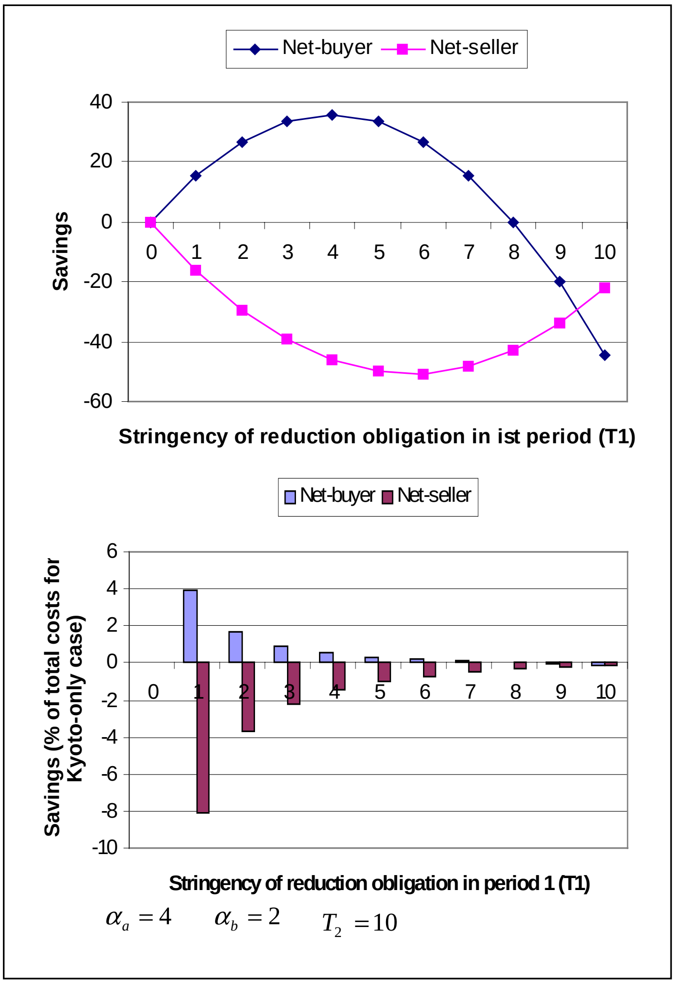
On the other hand the buying country would realise higher costs in the first period due to foregone benefits from trading if it realises the Kyoto-only approach (see $C_a^{(1)*}$ and $C_a^{(2)*}$ in Annex 7). These costs amount to

$$\Delta C^*_{a_1} = \alpha_a T_1^2 - \left[\alpha_a \left(\frac{2\alpha_b}{\alpha_a + \alpha_b} T_1 \right)^2 + \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} T_1 \; \frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_1 \right]$$

The question if $\Delta C^*_{a_2} - \Delta C^*_{a_1} > 0$ depends on the stringency of the reduction obligation in period 1 (see figure 3).

Figure 3

Implication of renouncing international trading in the first period compared to international trading without transfer of AAU in the first period with long living abatement options



As one can see in Fig. 3 expenses for permits in the second period are lower than additional costs in the first period as long as the reduction obligation is “weak” and as there is no trading in the first period. Consequently, country *a* would prefer the no Kyoto-only system to a no-AAU-transfer approach.

Table 2
Preferences for different approaches and stringency of reduction obligation under different design options for international emissions trading

	Lifetime of investment: 1 period		Lifetime of investment: both periods	
	Net-buyer	net-seller	net-buyer	net-seller
Support of different approaches				
Kyoto-only-trading	Low*)	Medium	medium**)	low
No-AAU-transfer	Medium*)	High	low	high
AAU-transfer	High	Low	high	medium
Preferred stringency of reduction obligation in period 1 for different approaches				
Kyoto-only-trading	Indifferent	Indifferent	Weak	Strong
No-AAU-transfer	Indifferent	Indifferent	Indifferent	Indifferent
AAU-transfer	Strong	Weak	Indifferent	Indifferent

*) Only if country is interested in cost-efficient international climate policy prior to 2008

**) As long as there are no strong reduction obligations in period 1

One can see that there is an inherent conflict of interests between seller and buyer with regard to the transfer of AAUs in international emissions trading prior to 2008. Against this background one may question whether governments will voluntarily decide to link their trading schemes prior to the first commitment period.

5 Summary

Before greenhouse gas emission trading can start on entity level, several design features have to be decided on. Linking of these national schemes can result in increase cost-efficiency. But as in sovereign nation states these decisions may differ, the linkage may be prevented for technical reasons or affect environmental integrity.

The analysis reveals that potential technical obstacles can likely be overcome inducing additional costs (this goes for example for differences in registry structures).

Environmental integrity may be affected easily. If this is to be avoided, systems would have to be adapted or linkage has to be abstained from.

The situation is, however, different from the economic point of view. Even though the overall cost-efficiency can be increased, the incidence of costs in the context of the Kyoto-regime, that may start in 2008, suggests that governments would refrain from linking their schemes voluntarily prior to 2008: Net-buyer and net-seller may have contrary interests with respect to the transfer of AAUs. This also means that a mandatory linkage as proposed by the European Commission is likely to produce winners and losers among member states. This in turn might provoke resistance by member states.

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ANNEX

Annex 1:

General version of (2)

$$\min_{R_{i1},R_{i2},P_{i1},P_{i2}} C_i = \alpha_{i1}R_{i1}^2 + \pi_1 P_{i1} + \frac{\alpha_{i2}R_{i2}^2}{1+\delta} + \frac{\pi_2 P_{i2}}{1+\delta}$$

s.t.

$R_{i1} + P_{i1} \geq E_{i0} + A_{i1}$; $R_{i2} + P_{i2} \geq E_{i0} + A_{i2}$

where δ = discount rate; E = Emissions; A = Permits allocated

Annex 2:

First order conditions for (1): Kyoto trading only

$$2\alpha_a R_{a1} - \lambda_{a1} = 0$$

$$2\alpha_a R_{a2} - \lambda_{a2} = 0$$

$$\pi_2 - \lambda_{a2} = 0$$

$$R_{a1} - T_1 = 0$$

$$R_{a2} + P_2 - T_2 = 0$$

$$2\alpha_b R_{b1} - \lambda_{b1} = 0$$

$$2\alpha_b R_{b2} - \lambda_{b2} = 0$$

$$-\pi_2 + \lambda_{b2} = 0$$

$$R_{b1} - T_1 = 0$$

$$R_{b2} - P_2 - T_2 = 0$$

Annex 3:

First order conditions for (2): Non AAUs-based PKU-tradings

$$2\alpha_a R_{a1} - \lambda_{a1} = 0$$
$$\pi_1 - \lambda_{a1} = 0$$
$$2\alpha_a R_{a2} - \lambda_{a2} = 0$$
$$\pi_2 - \lambda_{a2} = 0$$
$$R_{a1} + P_1 - T_1 = 0$$
$$R_{a2} + P_2 - T_2 = 0$$

$$2\alpha_b R_{b1} - \lambda_{b1} = 0$$
$$-\pi_1 + \lambda_{b1} = 0$$
$$2\alpha_b R_{b2} - \lambda_{b2} = 0$$
$$-\pi_2 + \lambda_{b2} = 0$$
$$R_{b1} - P_1 - T_1 = 0$$
$$R_{b2} - P_2 - T_2 = 0$$

Annex 4:

First order conditions for (4): AAUs-based PKU-tradings

$$2\alpha_a R_{a1} - \lambda_{a1} = 0$$
$$\pi_1 - \lambda_{a1} = 0$$
$$2\alpha_a R_{a2} - \lambda_{a2} = 0$$
$$\pi_2 - \lambda_{a2} = 0$$
$$R_{a1} + P_1 - T_1 = 0$$
$$R_{a2} + P_2 + P_1 - T_2 = 0$$

$$2\alpha_b R_{b1} - \lambda_{b1} = 0$$
$$-\pi_1 + \lambda_{b1} = 0$$
$$2\alpha_b R_{b2} - \lambda_{b2} = 0$$
$$-\pi_2 + \lambda_{b2} = 0$$
$$R_{b1} - P_1 - T_1 = 0$$
$$R_{b2} - P_2 - P_1 - T_2 = 0$$

Annex 5:

Cost functions in equilibrium (lifetime of investments: one period):

<u>Country a (net buyer):</u>

Kyoto trading only:

$$C_a^{(1)} = \alpha_a T_1^2 + \alpha_a \left(\frac{2\alpha_b}{\alpha_a + \alpha_b} T_2 \right)^2 + \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} T_2 \; \frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_2$$

No AAU-transfer:

$$C_a^{(2)} = \alpha_a \left(\frac{2\alpha_b}{\alpha_a + \alpha_b} T_1 \right)^2 + \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} T_1 \; \frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_1 + \alpha_a \left(\frac{2\alpha_b}{\alpha_a + \alpha_b} T_2 \right)^2 + \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} T_2 \; \frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_2$$

AAU-transfer:

$$C_a^{(3)} = \alpha_a \left(\frac{2\alpha_b}{\alpha_a + \alpha_b} T_1 \right)^2 + \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} T_1 \; \frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_1 + \alpha_a \left(\frac{2\alpha_b}{\alpha_a + \alpha_b} T_2 \right)^2 + \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} T_2 \left[\frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_2 + \frac{(\alpha_b - \alpha_a)}{\alpha_a + \alpha_b} T_1 \right]$$

$$C_a^{(1)} > C_a^{(2)} > C_a^{(3)}$$

<u>Country b (net seller):</u>

Kyoto-trading-only:

$$C_b^{(1)} = \alpha_b T_1^2 + \alpha_b \left(\frac{2\alpha_a}{\alpha_a + \alpha_b} T_2 \right)^2 - \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} T_2 \; \frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_2$$

No-AAU-transfer:

$$C_b^{(2)} = \alpha_b \left(\frac{2\alpha_a}{\alpha_a + \alpha_b} T_1 \right)^2 - \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} T_1 \; \frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_1 + \alpha_b \left(\frac{2\alpha_a}{\alpha_a + \alpha_b} T_2 \right)^2 - \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} T_2 \; \frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_2$$

AAU-transfer:

$$C_b^{(3)} = \alpha_b \left(\frac{2\alpha_a}{\alpha_a + \alpha_b} T_1 \right)^2 - \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} T_1 \; \frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_1 + \alpha_b \left(\frac{2\alpha_a}{\alpha_a + \alpha_b} T_2 \right)^2 - \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} T_2 \left[\frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_2 + \frac{(\alpha_b - \alpha_a)}{\alpha_a + \alpha_b} T_1 \right]$$

$$C_b^{(3)} > C_b^{(1)} > C_b^{(2)}$$

Annex 6:

Cost functions in equilibrium (Investments in emission reductions only induce costs once (in the period when implemented):

(1*)

$$\min_{R_{a1}^*, R_{a2}^*, P_2^*} C_a^* = \alpha_a R_{a1}^{*2} + \alpha_a R_{a2}^{*2} + \pi_2^* P_2^* ; \quad \min_{R_{b1}^*, R_{b2}^*, P_2^*} C_b^* = \alpha_b R_{b1}^{2*} + \alpha_b R_{b2}^{2*} - \pi_2^* P_2^*$$

s.t.

$$R_{a1}^* \geq T_1 \;;\; R_{b1}^* \geq T_1 \;;\; R_{a2}^* + P_2^* + R_{a1}^* \geq T_2 \;;\; R_{b2}^* - P_2^* + R_{b1}^* \geq T_2$$

(2*)

$$R_{a1}^* = T_1 \;;\; R_{b1}^* = T_1 \;;\; \lambda_{a1}^* = 2\alpha_a T_1 ;\; \lambda_{b1}^* = 2\alpha_b T_1 ;$$

$$R_{a2}^* = \frac{2\alpha_b}{\alpha_a + \alpha_b}(T_2 - T_1) ;\; R_{b2}^* = \frac{2a_a}{\alpha_a + \alpha_b}(T_2 - T_1) ;$$

$$\pi_2^* = \lambda_{a2}^* = \lambda_{b2}^* = \frac{4\alpha_a a_b}{\alpha_a + \alpha_b}(T_2 - T_1) ;\; P_2^* = \frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_2 + \frac{(\alpha_b - \alpha_a)}{\alpha_a + \alpha_b} T_1$$

One can see that the lifetime of the investment obviously influences the outcome. As can be seen in (2*) the permit price, the quantity traded[1] and the quantity abated in the second period decrease.

(3*)

$$\min_{R_{a1}^*, R_{a2}^*, P_1^*, P_2^*} C_a^* = \alpha_a R_{a1}^{*2} + \pi_1^* P_1^* + \alpha_a R_{a2}^{*2} + \pi_2^* P_2^* ;$$

$$\min_{R_{b1}, R_{b2}, P_1, P_2} C_b^* = \alpha_b R_{b1}^{*2} - \pi_1^* P_1^* + \alpha_b^* R_{b2}^{*2} - \pi_2^* P_2^*$$

s.t.

$$R_{a1}^* + P_1^* \geq T_1 \;;\; R_{b1}^* - P_1^* \geq T_1 \;;\; R_{a2}^* + P_2^* + R_{a1}^* \geq T_2 \;;\; R_{b2}^* - P_2^* + R_{b1}^* \geq T_2$$

1 Remember that $\alpha_b - \alpha_a < 0$ as by definition abatement costs are higher in country a.

(4*)

$$R_{a1}^* = \frac{2\alpha_b}{\alpha_a + \alpha_b} T_1 \ ; \ R_{b1}^* = \frac{2\alpha a_a}{\alpha_a + \alpha_b} T_1 \ ; \ \pi_1^* = \lambda_{a1}^* = \lambda_{b1}^* = \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} T_1 \ ;$$

$$P_1^* = \frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_1$$

$$R_{a2}^* = \frac{2\alpha_b}{\alpha_a + \alpha_b}(T_2 - T_1) \ ; \ R_{b2}^* = \frac{2\alpha_a}{\alpha_a + \alpha_b}(T_2 - T_1) \ ; \ \pi_2^* = \lambda_{a2}^* = \lambda_{b2}^* = \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b}(T_2 - T_1) \ ;$$

$$P_2^* = \frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_2$$

(5*)

$$R_{a1}^* + P_1^* \geq T_1 \ ; \ R_{b1}^* - P_1^* \geq T_1 \ ; \ R_{a2}^* + P_2^* + R_{a1}^* + P_1^* \geq T_2 \ ; \ R_{b2}^* - P_2^* + R_{b1}^* - P_1^* \geq T_2$$

(6*)

$$R_{a1}^* = \frac{2\alpha_b}{\alpha_a + \alpha_b} T_1 \ ; \ R_{b1}^* = \frac{2\alpha_a}{\alpha_a + \alpha_b} T_1 \ ; \ \pi_1^* = \lambda_{a1}^* = \lambda_{b1}^* = \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} T_1 \ ; \ P_1^* = \frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_1 \ ;$$

$$R_{b2}^* = \frac{2\alpha_a}{\alpha_a + \alpha_b}(T_2 - T_1) \ ; \ \pi_2^* = \lambda_{a2}^* = \lambda_{b2}^* = \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b}(T_2 - T_1) \ ;$$

$$P_2^* = \frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_2 + \frac{(\alpha_b - \alpha_a)}{\alpha_a + \alpha_b} T_1$$

Annex 7:

Substituting (2*), (4*) and (6*) in (1*), (3*) and (5*) respectively gives:

<u>Country a (net buyer):</u>

Kyoto-trading-only:

$$C_a^{(1)*} = \alpha_a T_1^2 + \alpha_a \left(\frac{2\alpha_b}{\alpha_a + \alpha_b} (T_2 - T_1) \right)^2 + \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} (T_2 - T_1) \left[\frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_2 + \frac{(\alpha_b - \alpha_a)}{\alpha_a + \alpha_b} T_1 \right]$$

No-AAU-transfer:

$$C_a^{(2)*} = \alpha_a \left(\frac{2\alpha_b}{\alpha_a + \alpha_b} T_1 \right)^2 + \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} T_1 \frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_1 + \alpha_a \left(\frac{2\alpha_b}{\alpha_a + \alpha_b} (T_2 - T_1) \right)^2 + \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} (T_2 - T_1) \frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_2$$

AAU-transfer:

$$C_a^{(3)*} = \alpha_a \left(\frac{2\alpha_b}{\alpha_a + \alpha_b} T_1 \right)^2 + \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} T_1 \frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_1 + \alpha_a \left(\frac{2\alpha_b}{\alpha_a + \alpha_b} (T_2 - T_1) \right)^2 + \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} (T_2 - T_1) \left[\frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_2 + \frac{(\alpha_b - \alpha_a)}{\alpha_a + \alpha_b} T_1 \right]$$

<u>Country b (net seller):</u>

Kyoto-trading-only:

$$C_b^{(1)*} = \alpha_b T_1^2 + \alpha_b \left(\frac{2\alpha_a}{\alpha_a + \alpha_b} (T_2 - T_1) \right)^2 - \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} (T_2 - T_1) \left[\frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_2 + \frac{(\alpha_b - \alpha_a)}{\alpha_a + \alpha_b} T_1 \right]$$

No-AAU-transfer:

$$C_b^{(2)*} = \alpha_b \left(\frac{2\alpha_a}{\alpha_a + \alpha_b} T_1 \right)^2 - \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} T_1 \frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_1 + \alpha_b \left(\frac{2\alpha_a}{\alpha_a + \alpha_b} (T_2 - T_1) \right)^2 - \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} (T_2 - T_1) \frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_2$$

AAU-transfer:

$$C_b^{(3)*} = \alpha_b \left(\frac{2\alpha_a}{\alpha_a + \alpha_b} T_1 \right)^2 - \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} T_1 \frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_1 + \alpha_b \left(\frac{2\alpha_a}{\alpha_a + \alpha_b} (T_2 - T_1) \right)^2 - \frac{4\alpha_a \alpha_b}{\alpha_a + \alpha_b} (T_2 - T_1) \left[\frac{(\alpha_a - \alpha_b)}{\alpha_a + \alpha_b} T_2 + \frac{(\alpha_b - \alpha_a)}{\alpha_a + \alpha_b} T_1 \right]$$