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Abatement Costs vs. Compliance Costs in Multi-Period Emissions Trading - The Firms' Perspective

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– The Firms’ Perspective**

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HWWA DISCUSSION PAPER

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HWWA Discussion Paper

Abatement Costs vs. Compliance Costs in Multi- Period Emissions Trading – The Firms' Perspective

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HWWA Discussion Paper 230

<http://www.hwwa.de>

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Abatement Costs vs. Compliance Costs in Multi- Period Emissions Trading – The Firms' Perspective

ABSTRACT:

Greenhouse gas emission trading has become more and more important in the context of climate change. Recently, a discussion on trading on entity (i.e. company) level has started. Emitters likely to be obliged to participate have argued for an initial allocation of the emission rights free of charge. I analyse the implication of such an allocation based on historical emissions and on benchmarks in multi-period emission trading. Different allocation rules for successive periods are applied, namely allocations with reference figures that are either constant or that change over time. The analysis is carried out using a two-player, two-period model. I find that – depending on their marginal abatement cost - participants have different preferences with regard to the allocation method over time as individual compliance cost can change, too. Total costs remain, however, unaffected by the individual allocations as emissions are reduced where abatement is cheapest. Furthermore, I show that, depending on the allocation method, incentives exist to increase emissions in one period in order to get more emission rights in a subsequent period.

JEL-Classifikation: H23, L20, Q25, Q28

Keywords: GHG abatement costs, allocation of emission rights, compliance costs, multi period emission trading,

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1 Introduction

In the context of the increasing awareness of a human induced climate change, emission trading as one possible instrument to reduce greenhouse gas (GHG) emissions has moved into the centre of the discussion in the last years. In the very beginning the instrument has been applied for other than GHG emissions especially in the US. In 1997 the Kyoto-Protocol was agreed upon that sets the framework for GHG emission trading on country level. Certain Parties to the Protocol are allowed to trade the so-called Assigned Amount Units (AAUs) in order to fulfil their obligations that are determined in absolute emissions compared to 1990 levels¹: For example, for the first five year commitment period starting in 2008 Germany is allowed to emit 79% of 1990's emissions whereas others as Australia may increase emission up to 108% of 1990 emissions.

A country can either make use of the so-called flexible mechanisms under the Protocol and buy emission rights abroad or reduce domestically by policies and measures (P&M). Among these P&Ms, market based instruments have attracted a lot of attention (especially by economists). For example, the European Commission suggested an European energy tax in the early '90s but it was never introduced. Only recently emission trading on entity level has become the focal point of the discussion. Numerous "governmental – industry working groups" were set up to discuss what a potential trading scheme involving private actors could look like (see for example AGE (2002), AGO (1999), MIES (2000), NZME (1998)). The most important step may be the proposal for a directive for a Europe-wide emission trading scheme proposed by the European Commission in 2001 (Com 2001a) that has been approved by the Council and the European parliament in the first with minor amendments in late 2002. A final decision is expected in 2003.

When creating national trading schemes a lot of design features have to be decided on. A very important point from the firms' perspective is the question of how the emission rights¹ will be allocated. This issue has been discussed in numerous studies (AGE (2002), AGO (1999), CCAP (2002), Field (2000), MIES (2000), NZME (1998)). However, they only address general issues or, in case they go into detail, they only consider a one period game and do not discuss the impact of different allocation options in subsequent commitment periods. This paper tries to shed some light on this issue: I analyse the implications of different allocation options for multi-period emission trading focussing on the total costs (i.e. efficiency of the

¹ The term emission right and allowance are used equivalently. Other authors talk about permits in this context. After the EU Commission has proposed a directive on emission trading this might be a bit misleading as the term "permit" is used in another sense in this directive (like a permission or approval).

instrument) as well as on the individual firms' compliance costs for an allowance selling and a buying firm respectively. Furthermore, potential incentives to increase output in one period in order to get more emission rights in a subsequent period are studied.

In the following chapter I briefly discuss general options for allocating emission rights. I then focus on an allocation based on historical emissions and on benchmarks using two-player two-period model. As the analytical solution is difficult to interpret, numerical examples are provided subsequently. Finally, the potential incentives mentioned above are studied.

2 Emission trading and Allocation of allowances

Emission trading² allows to meet an absolute emission target cost-efficiently. However, the answer to the question of who is bearing the costs is not incorporated in the instrument itself and has to be treated separately ("question of burden sharing"). Participants in the trading scheme can decide whether they want to abate emissions internally or to buy emission rights on the market. At the end of a period each emitter has to have at least as much allowances as he actually emitted into the atmosphere. The decision to buy allowances is driven by the question if in-house marginal abatement costs are lower than the allowance price. As each player faces this problem, marginal abatement costs are equalised among sources at the end of the period.

Before trading can start the participants have to be allocated a certain quantity of emission rights. Allowances may either be provided free of charge or charged. For trading on company level economists have argued in favour of a charged allocation or more precisely an auction as giving the allowances for free would result in an extra revenue for the receivers of the allowances (Cramton and Kerr (2002), Field (2000) p. 31, Woerdman (2002) p. 620). However, others have argued that this question can only be answered when comparing the concrete design of an auction (for example "How is the revenue from the auction recycled?") and a free of charge scheme respectively (for example Bohm (2002)). On the other hand, those who would be obliged to participate ask for an allocation free of charge (Com (2001b, p.2)) and the current status of discussion on the EU trading scheme also suggests that an allocation free of charge is likely to be the method of choice at least for the initial period. I focus on this method below.

² In this paper emission trading is used in the sense of a cap-and-trade system.

A very important point for the allocation of allowances in GHG trading schemes as it is understood in this paper, is that the total budget is more or less given by the commitments made under the Kyoto-Protocol.³ Consequently, a simple bottom-up approach – that is to say where individual allocation is made without reflecting the total budget constraint - does not seem appropriate.⁴ An adjustment with the national budget has to be made (top-down approach).⁵

2.1 Determining the share of emission allowances (static analysis)

The available quantity for all participants has to be distributed among participants somehow. One may think of

- Negotiations (for example: AGE (2001) p. 63)
 - might be impossible (regarding costs and time) due to high number of participants
 - might face little acceptance due to fear of cheating or “equity” issues
 - outcome and impacts difficult to assess
- Reference figure
 - Production (for example: NERA (2002) p. 31)
 - Questionable if focused only on the product itself as output is not inevitably related to emissions and may consequently lead to distortions: e.g. kWh from nuclear and lignite fired power plants; reference to specific plants would be necessary/reasonable.
 - Emission related in a certain year/period (for example: CCAP (2002) p. 17)
 - Benchmarks (for example: CCAP (2002) p. 17)
- Abatement Costs / Potential (Com (2001a) Annex III, (3))
 - Difficult to apply as the exact abatement costs are private knowledge of the emitters. A revelation mechanism would be desirable / necessary (as for example an auction), but in a free of charge setting hard to define.
- Others (e.g. turn over, employees etc.)

³ This is not really true for any trading before the entry into force of the Protocol. For a discussion see Bode (2003) and Rehdanz and Tol (2002)

⁴ Such an approach would indeed be possible if other sectors than the participating ones get a smaller share of available national budget. This might cause a lot of resistance by the other sectors as they would have to bear a stronger burden. This is why such an approach is not further considered.

⁵ In the context of the Kyoto-Protocol, the budget can be enlarged by the purchase of CERs/ERUs from CDM and JI-projects respectively. But as this induces additional costs that have to be borne by someone, it is not considered as an option: from the participants' point of view the total costs are most relevant regardless where they exactly accrue.

- Does not seem reasonable as these figures are, if at all, only slightly correlated to emissions and use of these figures could consequently lead to strong distributional effects.
- Any combination of these

Below I focus on an allocation based on historical emissions - what is often referred to as grandfathering⁶ - and on benchmarks that are both by far most frequently mentioned in the reports cited above.

A straightforward approach for an allocation based on historical emissions (grandfathering) could be: Emissions are allocated proportionately to the single emitters' share of the total emissions, formally:

$$(1) A_i = \frac{I_i q_i}{\sum_i I_i q_i} A \quad i = 1, 2, \dots, N$$

where A_i = emissions allowances allocated to company i ; I_i = emission intensity of company i ; q_i = output of company i ; A = total quantity of emission rights to be distributed to the participants.

For a general benchmark⁷ the allocation could look like shown in equation (2).⁸

$$(2) A_i = s q_i$$

$$\text{s.t. (3) } \sum_i A_i \leq A \quad i = 1, 2, \dots, N$$

where s = general specific emission factor (t CO₂/unit), q_i = output of company i (unit)

⁶ However, as emission reductions are still necessary for almost all Annex B countries, grandfathering can *generally* not mean distribution of emission rights equal to historical emissions (bottom-up approach) An adjustment according to the total budget available is necessary – or in other words: grandfathering is an allocation method based on historical emissions (top-down approach).

⁷ Theoretically, individual benchmarks for each emitter are conceivable. However, as there are already more than 4000 installations expected to participate in the initial phase of the EU-trading scheme, the use of such company specific benchmarks seems at least administratively infeasible.

⁸ When creating real world systems one should be aware of the fact that in case different sectors (heat and power, pulp and paper etc.) participate, different “sub-budget” for each benchmark have to be determined as specific emission factors are only applicable if the reference figure is used by all members of the subset.

2.2 Determining the share of emission rights in successive periods

Trading schemes can be designed as one-period as well as multi-period schemes where the latter option is much more likely to be realised. The allocation in successive periods can either be carried out on the basis of the initial allocation (what I refer to as *constant allocation*) or on the basis of data gathered in a period later than the initial one (what I refer to as *rolling allocation*). One might think of a constant base period as the intuitive approach. In this case the allocation for all periods is determined at the very beginning of the trading scheme. Thus, emitters that reduce emissions by more than their initial allocations are directly awarded with this approach as they have longer-term revenues from the sale of the allowances. However, the simple reduction of output for whatever reasons is also be beneficial with regard to the allowance balance. One might question whether it is desirable that a company, which changes its business portfolio, receives emission rights in 2050 on the basis of emissions it had released sometime in the 1990s. An approach in which the allocation in subsequent periods is based on more recent emissions (or output) rather than on the first one (i.e. a rolling allocation) may take this aspect into account. On the other hand, this could reduce the incentive to invest in in-house reductions as today's decision could influence the next periods' allocation: "The more you reduce now the less emission rights you get in the future". Edwards and Hutton (2001, p. 375) argue similarly stating: "However, if companies expect that, by emitting more now, they get a larger allowance allocation in the future, there would be a counterbalancing incentive to continue emitting".

So far the discussion of the allocation of emission rights has more or less neglected the question of future commitment periods. Boemare and Quirion (2002) for example analyse ten trading schemes in order to give some recommendations for the design of the European scheme. The issue of allocation over time is, however, not addressed. The same goes for Holmes and Friedmann (2000) who discuss design alternatives for a carbon trading scheme in the US and for Svendsen (1997) who focuses on Denmark. The issue is not addressed in the "governmental-industry reports" mentioned above either and also a recent paper on "how to develop a national allocation plan" by the European Commission (Com 2003) does not discuss this issue. CCAP (1999) focuses on the allocation of greenhouse gas reduction responsibilities but does not consider dynamic aspects and finally, UNEP et al. (2002 p. 14) states that the allocation rule can change over time without providing a more detailed analysis. On the other hand, rolling allocations have been used in general equilibrium analyses of the impact of different allocation options on the *large scale economy*. However, due to this

intention they cannot answer the individual firm's perspective. For example, Jensen and Rasmussen (2000) allocate emission rights to the firms in a certain period, inter alia, according to the market share in the previous period. Edwards and Hutton (2001) apply a regular updated benchmark (a variant of the "best-practice" approach) and find that this approach would even improve GDP and welfare compared to other approaches that were analysed (auction and grandfathering). Unfortunately, it remains unclear whether the top-down alignment was done. Nera analysed a so-called *updating* approach where the allocation is based on the output in different periods (Nera (2002) pp. 25-30). Unfortunately, they do not consider (changing) emissions as a basis for allocation nor do they analyse the individual company's point of view. To sum it up, a systematic analysis of the different options and the resulting impacts on a seller and buyer is missing. I try to increase the understanding of this issue below.

When analysing successive periods we have to add a time index and to rewrite equations (1) – (3) as follows:

$$(4) \quad A_{i,t} = \frac{I_{i,t-j} q_{i,t-j}}{\sum_i I_{i,t-j} q_{i,t-j}} * A_t \quad i = 1, 2, \dots, N ; t = 1, 2, \dots, T ; j = 1, 2, \dots, T$$

$$(5) \quad A_{i,t} = s_{t-j} * q_{i,t-j}$$

$$\text{s.t. (6) } \sum_i A_{i,t} \leq A_t \quad i = 1, 2, \dots, N ; t = 1, 2, \dots, T$$

In the following section a general model for an analytical analysis of the different allocation options is introduced before a numerical approach is used to study the impacts.

3 The Model

In order to analyse the impact of different allocation options on the participants let us consider a two-player, two-period market, in which the emitters face different abatement costs (which are assumed to be quadratic in the reduction technologies implemented). Let us denote the buying firm with the index a and the firm with the lower abatement costs (seller) with the index b . No banking between the periods is allowed. The lifetime of the investment is one

period⁹, so that each firm can decide¹⁰ on the abatement level in each period independently. I distinguish between two abatement technologies: a) An end-of-pipe approach¹¹, that is to say specific emissions during production do not change. Emissions are rather removed at the end of the production chain. b) Improvement of the emission intensity of the production.

As – especially with the rolling allocation approach – the number of permits allocated in the second period may depend on the emissions (and thus on the emission reductions) in the first period, the two players minimise costs over both periods already at the very beginning of the trading scheme. Transaction costs are neglected. They face the optimisation problem:

$$(7) \quad \min_{R_{a1}, R_{a2}, P_1, P_2} C_a = \alpha_{a1} R_{a1}^2 + \pi_1 P_1 + \frac{\alpha_{a2} R_{a2}^2}{1 + \delta} + \frac{\pi_2 P_2}{1 + \delta} ;$$

$$\min_{R_{b1}, R_{b2}, P_1, P_2} C_b = \alpha_{b1} R_{b1}^2 - \pi_1 P_1 + \frac{\alpha_{b2} R_{b2}^2}{1 + \delta} - \frac{\pi_2 P_2}{1 + \delta}$$

where, C = Costs, α = parameter, R = investment in in-house abatement technologies (t CO₂-eq), π = allowance price (assuming a perfect market where each participant faces the same price), P = quantity of allowances bought or sold, δ = discount factor

3.1 Abatement by end-of-pipe technologies

When using an end-of-pipe technology the emitters have to consider the constraints

$$(8) \quad R_{at} + P_{at} \geq I_a q_{at} - A_{at} ; R_{bt} - P_{bt} \geq I_b q_{bt} - A_{bt} \quad t = 1,2$$

index 1;2 = period one and two respectively, I = Emission, q = output (product) A = allocation

As mentioned an allocation based on emissions as well as on benchmarks is studied.

3.1.1 Allocation based on historical emissions

3.1.1.1 Constant allocation

In the case of a constant allocation based on emissions the individual allocation would be:

⁹ As long as the total reduction obligation (i.e. total expected emissions minus total budget of allowances) is equal or less in the following periods, each emitter reduces at least as much as he did in the preceding period so that the affect could be interpreted as a lifetime of two periods for those reductions undertaken in the first period and additional reductions in the second one.

¹⁰ Indeed, emitters do not really decide about their reduction level. In a perfect market, as is assumed here, reductions are rather prescribed by the total reduction obligation and the marginal cost curves of the different players.

¹¹ As for example carbon dioxide removal from flue gases.

$$(4a) \quad A_{i,t} = \frac{I_{i,0}q_{i,0}}{\sum_i I_{i,0}q_{i,0}} * A_i \quad i = a, b ; t = 1, 2$$

Minimising eq. (7), (8) and (4a) gives

$$(9) \quad R_{a1} = \frac{\alpha_b(I_a q_{a1} + I_b q_{b1} - A_1)}{\alpha_b + \alpha_a}, \quad R_{b1} = \frac{\alpha_a(I_a q_{a1} + I_b q_{b1} - A_1)}{\alpha_b + \alpha_a},$$

$$P_1 = \frac{I_a^2 q_a \alpha_a^* + I_a q_{a1} I_b q_{b0} \alpha_a - I_a q_{a0} A_1 \alpha_a - I_a q_{a0} I_b q_{b1} \alpha_b - I_b^2 q_b^* \alpha_b + I_b q_{b0} A_1 \alpha_b}{(I_a q_{a0} + I_b q_{b0})(\alpha_a + \alpha_b)}$$

$$\pi_1 = \lambda_{b1} = \lambda_{b1} = 2 \frac{\alpha_a(I_a q_{a1} + I_b q_{b1} - A_1)}{\alpha_b + \alpha_a}, \quad R_{a2} = \frac{\alpha_b(I_a q_{a2} + I_b q_{b2} - A_2)}{\alpha_b + \alpha_a},$$

$$R_{b2} = \frac{\alpha_a(I_a q_{a2} + I_b q_{b2} - A_2)}{\alpha_b + \alpha_a},$$

$$P_2 = \frac{I_a^2 q_{a0} q_{a2} \alpha_a + I_a q_{a2} I_b q_{b0} \alpha_a - I_a q_{a0} A_2 \alpha_a - I_a q_{a0} I_b q_{b2} \alpha_b - I_b^2 q_{b0} q_{a2} \alpha_b + I_b q_{b0} A_2 \alpha_b}{(I_a q_{a0} + I_b q_{b0})(\alpha_a + \alpha_b)}$$

$$\lambda_{a2} = \lambda_{b2} = 2 \frac{\alpha_a \alpha_b (I_a q_{a2} + I_b q_{b2} - A_2)}{(\alpha_b + \alpha_a)(1 + \delta)}, \quad \pi_2 = 2 \frac{\alpha_a \alpha_b (I_a q_{a2} + I_b q_{b2} - A_2)}{\alpha_b + \alpha_a}$$

We see that the problem is nearly symmetrical for both periods. Marginal abatement costs in period one and two differ by the discount factor. Other differences may occur in case the output and thus emissions changes over time.

3.1.1.2 Rolling base period

A rolling period means that allocation is done on the basis of a period later than the initial one (i.e. $j < t$). For example one may allocate emission rights for the period 2005-2008 based on emissions in 1998-2000 and for the subsequent period 2008-2012 on emissions in 2003-2005.

In the case of a rolling allocation based on (historical) emissions the individual allocation would be:

$$(4b) \quad A_{i,t} = \frac{I_{i,t-1}q_{i,t-1}}{\sum_i I_{i,t-1}q_{i,t-1}} * A_i \quad i = a, b ; t = 1, 2$$

With a rolling allocation (7), (8) and (4b) minimise as (9) except for P_2 which is:

$$(9b) \quad P_2 = \frac{I_a q_{a2} \alpha_a A_1 + I_b q_{b1} \alpha_b A_2 - I_b q_{b2} \alpha_b A_1 - I_a q_{a1} \alpha_a A_2}{A_1 (\alpha_b + \alpha_a)}$$

We can see that, unlike in the case with constant allocation, the quantity traded in period two is dependent on the total budget of period one (A_1). This seems to be sound as the total budget in period one determines the players' reductions (and thus emissions) in period one that (can) in turn form the basis for the allocation in period two.

3.1.2 Allocation based on benchmarks

In this analysis the term "benchmark" is used in the sense of a specific emission factor, i.e.

$$\frac{\text{emissions}}{\text{output}}^{12}$$

As mentioned above, the allocation based on a general benchmark could be calculated as

$$(5) \quad A_{i,t} = s_{t-j} * q_{i,t-j}$$

As already pointed out above an alignment between bottom-up (benchmark) approach and top-down constraint would be necessary to consider the constraint given in inequality (6). A straightforward approach would be the introduction of a correction factor as discussed for example in AGE (2002)

$$c_t = \frac{A_t}{\sum_i A_{i,t}} \quad t = 1,2$$

Taking into account this factor, (5) changes to

$$(10) \quad A_{i,t} = s_{t-j} * q_{i,t-j} * c_t \Leftrightarrow A_{i,t} = s_{t-j} q_{i,t-j} \frac{A_t}{\sum_i A_{i,t}} \Leftrightarrow A_{i,t} = s_{t-j} q_{i,t-j} \frac{A_t}{\sum_i s_{t-j} q_{i,t-j}}$$

$$\Leftrightarrow A_{i,t} = q_{i,t-j} \frac{A_t}{\sum_i q_{i,t-j}}$$

As we can see by transforming equation (10), a benchmark based allocation, that takes into account the national budget (e.g. the Kyoto Commitment), results in an individual allocation that is only proportional to a participant's output and not at all related to emission intensities.

¹² Theoretically, any benchmark as, for example, labour productivity could be used for allocation. For an emission benchmark, other reference figures than the output could also be used (e.g. turnover).

This might be somewhat surprising as the intention of the use of a benchmark is generally to consider the specific emissions.¹³

3.1.2.1 Constant allocation

For constant allocation the individual emitter gets allowances amounting to

$$(10a) \quad A_{i,t} = q_{i,0} \frac{A_t}{\sum_i q_{i,0}} \quad t = 1,2$$

Again (7), (8) and (10a) minimise as (9) except for P_1 and P_2 which are:

$$(9c) \quad P_1 = \frac{I_a q_{a0} q_{a1} \alpha_a - q_{a0} A_1 \alpha_a - I_b q_{a0} q_{b1} \alpha_b + q_{b0} A_1 \alpha_b - I_b q_{b0} q_{b1} \alpha_b + I_a q_{a1} q_{b0} \alpha_a}{(q_{a0} + q_{b0})(\alpha_a + \alpha_b)},$$

$$(9d) \quad P_2 = \frac{I_a q_{a0} q_{a2} \alpha_a - q_{a0} A_2 \alpha_a - I_b q_{a0} q_{b2} \alpha_b + q_{b0} A_2 \alpha_b - I_b q_{b0} q_{b2} \alpha_b + I_a q_{a2} q_{b0} \alpha_a}{(q_{a0} + q_{b0})(\alpha_a + \alpha_b)}$$

As we can see, the quantity traded depends on the total budget of allowances available in the period analysed, the output, the intensity and the parameters α .

3.1.2.2 Rolling allocation

With a rolling allocation the individual budget amounts to:

$$(10b) \quad A_{i,t} = q_{i,t-1} \frac{A_t}{\sum_i q_{i,t-1}} \quad t = 1,2$$

(7), (8) and (10b) solve as (9) except for the quantity traded in each period:

$$(9e) \quad P_1 = \frac{I_a q_{a0} q_{a1} \alpha_a - q_{a0} A_1 \alpha_a - I_b q_{a0} q_{b1} \alpha_b + q_{b0} A_1 \alpha_b - I_b q_{b0} q_{b1} \alpha_b + I_a q_{a1} q_{b0} \alpha_a}{(q_{a0} + q_{b0})(\alpha_a + \alpha_b)},$$

$$(9f) \quad P_2 = \frac{I_a q_{a1} q_{a2} \alpha_a - q_{a1} A_2 \alpha_a - I_b q_{a1} q_{b2} \alpha_b + q_{b1} A_2 \alpha_b - I_b q_{b1} q_{b2} \alpha_b + I_a q_{a2} q_{b1} \alpha_a}{(q_{a1} + q_{b1})(\alpha_a + \alpha_b)}$$

¹³ Compliance costs can of course differ, but not as a consequence of different allocations but rather as a consequence of different abatement costs (see also numerical examples below).

As one might have expected, the quantity traded in the first period equals the one with a constant benchmark approach whereas the one traded in the second period changes in that it is also dependent on the available budget in this period and the output in period one.

3.2 Abatement by improvement of emission intensity

When improving emission intensity of the production in order to reduce emission the output is not only relevant for calculating the emissions (see r.h.s of inequality (8)) but also for the reduction (see l.h.s. of (8a)). The two emitters now face the constraints

$$(8a) \quad R_{at}q_{at} + P_{at} \geq I_a q_{at} - A_{at} \quad ; \quad R_{bt}q_{bt} + P_{bt} \geq I_b q_{bt} - A_{bt} \quad t = 1,2$$

where R = investment in in-house improvement of emission intensity (in t CO₂-eq/ unit)

The allocation remains unaffected by the change of the abatement technology. (4a, 4b, 10a, 10b are the same.)

3.2.1 Allocation based on historical emissions

3.2.1.1 Constant allocation

Minimising eq. (7), (8a) and (4a) gives

(9g)

$$R_{a1} = \frac{\alpha_b(I_a q_{a1} + I_b q_{b1} - A_1)}{\alpha_b q_{a1} + \alpha_a q_{b1}} \quad , \quad R_{b1} = \frac{\alpha_a(I_a q_{a1} + I_b q_{b1} - A_1)}{\alpha_b q_{a1} + \alpha_a q_{b1}} \quad ,$$

$$P_1 = \frac{I_a^2 q_{a0} q_{a1} \alpha_a q_{b1} + I_a q_{a1} I_b q_{b0} \alpha_a q_{b1} - I_a q_{a0} A_1 \alpha_a q_{b1} - I_a q_{a0} I_b q_{b1} \alpha_b q_{a1} - I_b^2 q_{b0} q_{a1} \alpha_b q_{a1} + I_b q_{b0} A_1 \alpha_b q_{a1}}{(I_a q_{a0} + I_b q_{b0})(\alpha_b q_{a1} + \alpha_a q_{b1})}$$

$$\pi_1 = \lambda_{b1} = \lambda_{b1} = 2 \frac{\alpha_a \alpha_b (I_a q_{a1} + I_b q_{b1} - A_1)}{\alpha_b q_{a1} + \alpha_a q_{b1}} \quad ,$$

$$R_{a2} = \frac{\alpha_b(I_a q_{a2} + I_b q_{b2} - A_2)}{\alpha_b q_{a2} + \alpha_a q_{b2}} \quad , \quad R_{b2} = \frac{\alpha_a(I_a q_{a2} + I_b q_{b2} - A_2)}{\alpha_b q_{a2} + \alpha_a q_{b2}} \quad ,$$

$$P_2 = \frac{I_a^2 q_{a0} q_{a2} \alpha_a q_{b2} + I_a q_{a2} I_b q_{b0} \alpha_a q_{b2} - I_a q_{a0} A_2 \alpha_a q_{b2} - I_a q_{a0} I_b q_{b2} \alpha_b q_{a2} - I_b^2 q_{b0} q_{a2} \alpha_b q_{a2} + I_b q_{b0} A_2 \alpha_b q_{a2}}{(I_a q_{a0} + I_b q_{b0})(\alpha_b q_{a2} + \alpha_a q_{b2})}$$

$$\lambda_{a2} = \lambda_{b2} = 2 \frac{\alpha_a \alpha_b (I_a q_{a2} + I_b q_{b2} - A_2)}{(\alpha_b q_{a2} + \alpha_a q_{b2})(1 + \delta)} \quad , \quad \pi_2 = 2 \frac{\alpha_a \alpha_b (I_a q_{a2} + I_b q_{b2} - A_2)}{\alpha_b q_{a2} + \alpha_a q_{b2}}$$

We see that the problem solves nearly symmetrically for both periods. Marginal abatement costs in period one and two differ by the discount factor. Other differences may occur in case the output and thus emissions change over time.

3.2.1.2 Rolling base period

With a rolling allocation (7), (8a) and (4b) minimises as (9g) except for P_2 which is:

(9h)

$$P_2 = \frac{-q_{\sim}A_* + q_{b\#}q_{a1}\alpha_*I_{b\#} + q_{b2}I_{b\#}q_{a\#}\alpha_b^2 + q_{b2}q_{a\#}\alpha_*I_{a^*} + q_{b\#}q_{a2}\alpha_a^2I_{a^*} - q_{b\#}q_{a1}\alpha_a^2I_{a\#2} - q_{b1}q_{a\#}\alpha_*I_{a\#} - q_{b2}q_{a\#}\alpha_b^2I_{b^*} - q_{a2}q_{b\#}\alpha_*I_{b^*} - q_{\wedge}A_*}{A_1(\alpha_b q_{a2} + \alpha_a q_{b2})(\alpha_b q_{a1} + \alpha_a q_{b1})}$$

where $A_* = \alpha_a \alpha_a A_1 A_2$, $q_{\sim} = q_{b2}q_{a1}$, $\alpha_* = \alpha_a \alpha_b$, $q_{a\#} = q_{a1}q_{a2}$, $q_{a\#} = q_{b1}q_{b2}$, $I_{a\#} = I_a A_2$, $I_{b\#} = I_b A_2$, $I_{a^*} = I_a A_1$,

$I_{a^*} = I_a A_1$, $q_{\wedge} = q_{b1}q_{a2}$

3.2.2 Allocation based on benchmarks

The characteristics / implications of a general benchmark have been discussed during the analysis of the end-of-pipe technology. They equally apply in the case of reductions by the improvement of the emission intensity.

3.2.2.1 Constant allocation

Again (7), (8a) and (10a) minimises as (9g) except for P_1 and P_2 which are:

(9i)

$$P_1 = \frac{I_a q_{a0} q_{a1} q_{b1} \alpha_a - q_{a0} q_{b1} A_1 \alpha_a - I_b q_{a0} q_{b1} q_{a1} \alpha_b + q_{b0} q_{a1} A_1 \alpha_b - I_b q_{b0} q_{b1} q_{a1} \alpha_b + I_a q_{a1} q_{b0} q_{b1} \alpha_a}{(q_{a0} + q_{b0})(\alpha_a q_{b1} + \alpha_b q_{a1})},$$

$$P_2 = \frac{I_a q_{a0} q_{a2} q_{b2} \alpha_a - q_{a0} q_{b2} A_2 \alpha_a - I_b q_{a0} q_{b2} q_{a2} \alpha_b + q_{b0} q_{a2} A_2 \alpha_b - I_b q_{b0} q_{a2} q_{b2} \alpha_b + I_a q_{a2} q_{b0} q_{b2} \alpha_a}{(q_{a0} + q_{b0})(\alpha_a q_{b1} + \alpha_b q_{a1})}$$

As we can see the quantity traded only changes with the change of the total budget of allowances available and the output of the emitters in the period analysed.

3.2.2.2 Rolling allocation

For the rolling allocation (7), (8a) and (10b) minimises as (9g) apart from P_2 which is:

(9f)

$$P_2 = \frac{I_a q_{a1} q_{a2} q_{b2} \alpha_a - q_{a1} q_{b2} A_2 \alpha_a - I_b q_{a1} q_{b2} q_{a2} \alpha_b + q_{b1} q_{a2} A_2 \alpha_b - I_b q_{b1} q_{b2} q_{a2} \alpha_b + I_a q_{a2} q_{b1} q_{b2} \alpha_a}{(q_{a1} + q_{b1})(\alpha_a q_{b2} + \alpha_b q_{a2})}$$

As one might have expected, the quantity traded in the first period equals the one with a constant benchmark approach whereas the one traded in the second period changes in that it is dependent on the available budget in this period and the output in period one and two.

4 Numerical Analysis

As the difference between the approaches is not obvious from the analytical solution I analyse some numerical examples. Three scenarios for each technology (end-of-pipe reductions and intensity improvement) are presented.

I study certain cases by presenting the solution in detail in order to understand the players' actions assuming that they minimise costs as a function of the output which is exogenously given (non-strategic behaviour). Following this, I try to find out whether there are incentives to vary output in period one in order to get a more beneficial allocation in the subsequent period (strategic behaviour).

4.1 Non strategic behaviour

In this section the market is analysed assuming that each player minimises his costs depending on an exogenously given output. Throughout this analysis the total budget in period one and two respectively as well as the parameter α_i are kept constant. Only output and emission intensities are changed.

4.1.1 Equal emission intensities

The first analysis is based on the values given Tab. 1. The corresponding results of the model are presented in Tab. 2. Tab. 3 and 4 summarise the preferences of the two players when the output changes. The underlying tables for the determination of the preferences can be found in the annex (Tab. A1 to A5). As can be seen, emission intensities are equal for both player in the first analysis.

Tab. 1: Values used for scenario analysis

Name	Symbol	Period 0 (base period)	Period 1	Period 2
Total Budget	A	/	38	36
Emission Intensity (a)	I_a	2	2	2
Emission Intensity (b)	I_a	2	2	2
Parameter	α_a	/	4	4
Parameter	α_b	/	2	2

Values have been chosen more or less arbitrarily. The only condition is $\alpha > \beta$ as long as player a is supposed to have the higher abatement costs.

Tab. 2: Impact of different allocation options over time with constant output for both players and reductions by end-of-pipe technology

Name	Symbol	Period 0			Period 1			Period 2 (emission based)			Period 2 (benchmark)			
		Constant	Rolling	Change	Constant	Rolling	Change	Constant	Rolling	Change	Constant	Rolling	Change	
<u>Output</u>														
Output (a)	q_a	10	10	10	/	10	10	/	10	10	/	10	10	/
Output (b)	q_b	10	10	10	/	10	10	/	10	10	/	10	10	/
<u>Emissions</u>														
Emissions (a)	$I_a q_a$	20	19,33	19,33	0	18,67	18,67	0,00	18,67	18,67	0,00	18,67	18,67	0,00
Emissions (b)	$I_b q_b$	20	18,67	18,67	0	17,33	17,33	0,00	17,33	17,33	0,00	17,33	17,33	0,00
Total (a+b)	/	40	38,00	38,00	0	36,00	36,00	0,00	36,00	36,00	0,00	36,00	36,00	0,00
<u>Allocation</u>														
Allocation (a)	A_a	/	19,00	19,00	0	18,00	18,32	0,32	18,00	18,00	0,00	18,00	18,00	0,00
Allocation (b)	A_b	/	19,00	19,00	0	18,00	17,68	-0,32	18,00	18,00	0,00	18,00	18,00	0,00
<u>The Market</u>														
Allowance price	π	/	5,33	5,33	0	10,67	10,67	0,00	10,67	10,67	0,00	10,67	10,67	0,00
Allowances traded	P	/	0,33	0,33	0	0,67	0,35	-0,32	0,67	0,67	0,00	0,67	0,67	0,00
Reductions (a)	R_a	/	0,67	0,67	0	1,33	1,33	0,00	1,33	1,33	0,00	1,33	1,33	0,00
Reductions (b)	R_b	/	1,33	1,33	0	2,67	2,67	0,00	2,67	2,67	0,00	2,67	2,67	0,00
<u>Costs (a)</u>														
Reductions	$\alpha_a R_a^2$	/	1,78	1,78	0	7,11	7,11	0,00	7,11	7,11	0,00	7,11	7,11	0,00
Allowances	πP	/	1,78	1,78	0	7,11	3,74	-3,37	7,11	7,11	0,00	7,11	7,11	0,00
Total (a)	C_a	/	3,56	3,56	0	14,22	10,85	-3,37	14,22	14,22	0,00	14,22	14,22	0,00
<u>Costs (b)</u>														
Reductions	$\alpha_b R_b^2$	/	3,56	3,56	0	14,22	14,22	0,00	14,22	14,22	0,00	14,22	14,22	0,00
Allowances	πP	/	-1,78	-1,78	0	-7,11	3,74	3,37	-7,11	-7,11	0,00	-7,11	-7,11	0,00
Total (b)	C_b	/	1,78	1,78	0	7,11	10,48	3,37	7,11	7,11	0,00	7,11	7,11	0,00
Total (a+b)	/	/	5,33	5,33	0	21,33	21,33	0,00	21,33	21,33	0,00	21,33	21,33	0,00

Figures and letters are explained below.

Discussion:

For the discussion of the result shown in Tab. 2 we concentrate on the second period: The different allocation options start to be effective at that time. Total emissions for both players are equal to the total budget as given in Tab. 1 (point 1)). As by emission trading emissions are reduced where it is cheapest, reductions by both player are the same for both a constant and a rolling allocation (point 2)). Consequently, total costs do not change by choosing different allocation options for the same total reduction obligation (point 2)) since the abatement cost curves are not affected by the initial allocation.

What can indeed be affected are the players' compliance costs. In the first period there is no change in the individual compliance costs with varying approaches.. In the second period, i.e. when the rolling approach starts being effective, compliance costs may, however, change considerably. Only when the output is constant, there is no difference in the second period for the benchmark allocation. This is due to the fact that the allocation is only a function of the output (see section on general benchmark) that is kept constant.

With an emission-based allocation the situation is different. As player *a* reduces less emissions in the first period due to the higher abatement costs compared to *b* (point A)), he gets more allowances in the second period (point B)) what in turn reduces his compliance costs. The opposite is true for player *b*. Driven by the market, he reduces more in the first period than *a* – resulting in a reduced allocation and higher compliance costs in period two (point C)).

The situation is different when output changes. Then, the benchmark approach delivers another outcome in the second period, too (see tables in the annex). With the buyer growing, he prefers the rolling benchmark allocation to a constant one. For the scenarios studied¹⁴, however, player *a* (buyer) prefers the rolling emission based allocation to the rolling benchmark in absolute terms. Obviously, with the model set-up chosen, there is no incentive for the player with the lower abatement costs to renounce investments in the first period to avoid reduced allocation in the second one with a rolling allocation. His cost minimising strategy is to invest anyhow.

To sum it up, seller and buyer do have different preferences with regard to the design of the scheme that are summarised in Tab. 3 and 4.

Even though overall ranking of preferences are dependent on the reduction technology applied it can be seen, that – with equal emission intensities (!) - the net buyer always prefers

¹⁴ A number of scenarios with different parameters than those given in Tab. 1 have been studied.

the emission based rolling allocation that in turn (as it is a zero sum game) ranks lowest in the seller's priority.

Tab. 3: Preferences with reductions by end-of-pipe technology and varying output and equal initial emission intensities

	Player a		Player b			
	Output (a/b)		Output (a/b)			
	constant / constant	growing / constant	Constant / growing	constant / constant	growing / constant	constant / growing
1. Priority	emi / rol	emi / rol	emi / rol	all other	emi / const & bm / const	bm / rol
2. Priority	all other	bm / rol	emi / const & bm / const	emi / rol	bm / rol	emi / const & bm / const
3. Priority		emi / const & bm / const	bm / rol		emi / rol	emi / rol

emi = emission based allocation, bm = benchmark allocation, const = constant allocation, rol = rolling allocation

Tab. 4: Preferences with reductions by end-of-pipe technology and varying output and equal initial emission intensities

	Player a		Player b			
	Output (a/b)		Output (a/b)			
	constant / constant	growing / constant	constant / growing	constant / constant	growing / constant	constant / growing
1. Priority	emi / rol	emi / rol	emi / rol	all other	bm / rol	emi / const & bm / const
2. Priority	all other	emi / const & bm / const	bm / rol	emi / rol	emi / const & bm / const	bm / rol
3. Priority		bm / rol	emi / const & bm / const		emi / rol	emi / rol

emi = emission based allocation, bm = benchmark allocation, const = constant allocation, rol = rolling allocation

4.1.2 Different emission intensities

In this chapter different emission intensities for the two players are analysed. I presume that the intensity of the player with the lower abatement cost curve is the higher one. One may argue that he has not undertaken any action to reduce emissions yet and that there are still some "low hanging fruits".

The total compliance costs that determine the preferences are exemplarily shown for the case of reductions by end-of-pipe technology and constant output in Tab. 5.

Tab. 5: Compliance costs (both periods) with different initial emission intensity for player b with constant output and reductions by end-of-pipe technology.^{*)}

Emission intensity player b ^{**)} (I_b)	Total (a+b)	Player a				Player b			
		emi/const	emi/rol	bm/const	bm/rol	emi/const	emi/rol	bm/const	bm/rol
2,1	45,33	29,12	23,26	23,26	23,26	16,22	22,07	22,07	22,07
2,2	69,33	42,92	34,26	29,21	29,21	26,41	35,07	40,13	40,13
2,3	98,67	58,89	47,24	35,45	35,45	39,77	51,42	63,21	63,21
2,4	133,33	76,77	62,07	41,86	41,86	56,57	71,26	91,47	91,47
2,5	173,33	96,30	78,61	48,30	48,30	77,04	94,72	125,04	125,04

emi = emission based allocation, bm = benchmark allocation, const = constant allocation, rol = rolling allocation

^{*)} Values for parameters as in Tab. 1, $q_{a1} = q_{b1} = q_{a2} = q_{b2} = 10$

^{**)} Other cases are presented in the annex.

Opposed to the situation with equal emission intensities there is no clear preference discernible as it differs depending the concrete intensity assumed. However, a general tendency can be observed that is depicted in Fig. 1. (see Tab. A6 to A10 in the annex).

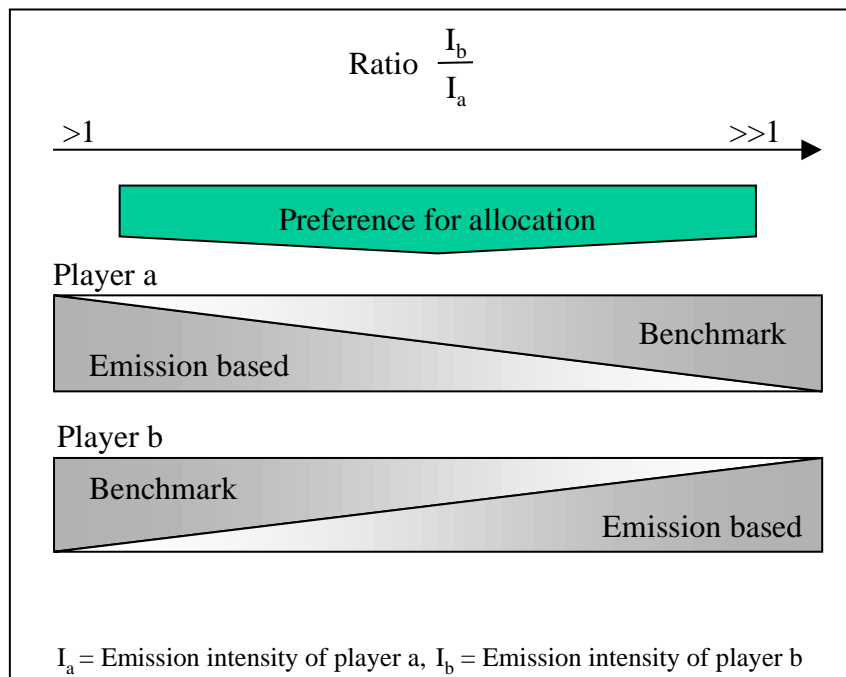


Fig 1: Tendency for preferences for different allocation options with different emission intensities.

The preferences shown in Fig. 1 can be explained as follows. With higher emission intensities (and the same output) player *b* has an increasing share of the total emissions and thus receives an increasing part of the total allowances with an emission-based allocation. The opposite is true for player *a*: With higher intensities for player *b* he prefers the benchmark allocation.

This is because these intensities are not relevant for the allocation at all (which rather depends on the output only)whereas he would receive less emission rights with an emission-based approach.

With very high intensities for player b , he even becomes a net-buyer. This is because any player first has to meet his emission target before he can sell any surplus allowances. If the reduction obligation (i.e. emissions minus allocation) becomes too big, marginal abatement costs at the point of meeting the target are too high even he has an abatement cost curve that is more flat than the one of player a . The general preferences shown above remain unaffected.

4.2 Strategic behaviour

As mentioned above, Edwards and Hutton (2001, p. 375) stated that “however, if companies expect that, by emitting more now, they get a larger allowance allocation in the future, there would be a counterbalancing incentive to continue emitting”. In this part, I want to focus on this issue. An incentive for one of the players would be given if total costs over both periods would be lower for one of them in case he increases his emissions in the first period. This can be done differently. A player may for example decide to increase production / stock in the first period (and thus emissions) to get more allowances in the second one. However, one has to keep in mind that the allocation in the first period remains unaffected of any of such consideration. Thus, increased output (emissions) in the first period would entail increased costs for the additional emissions, too. Alternatively, he may decide to intentionally decrease efficiency to increase emissions. Below, the first option is analysed.

It is modelled as follows: once a player has decided to increase stock¹⁵ (emissions), every participant minimises costs under the new conditions (i.e. equation (7), the different constraints as well as the different allocation options apply as in the parts above). The number of units produced in addition to the reference case ($q_{a1} = q_{b1} = 10$) in the first period is deducted from those in the second period (q_{a2} / q_{b2}) so that the sum for each player is always constant ($q_{a1} + q_{a2} = q_{b1} + q_{b2} = 20$).

Fig. 2 to 5 show the results for one player changing output.

¹⁵ Storage charges are not considered.

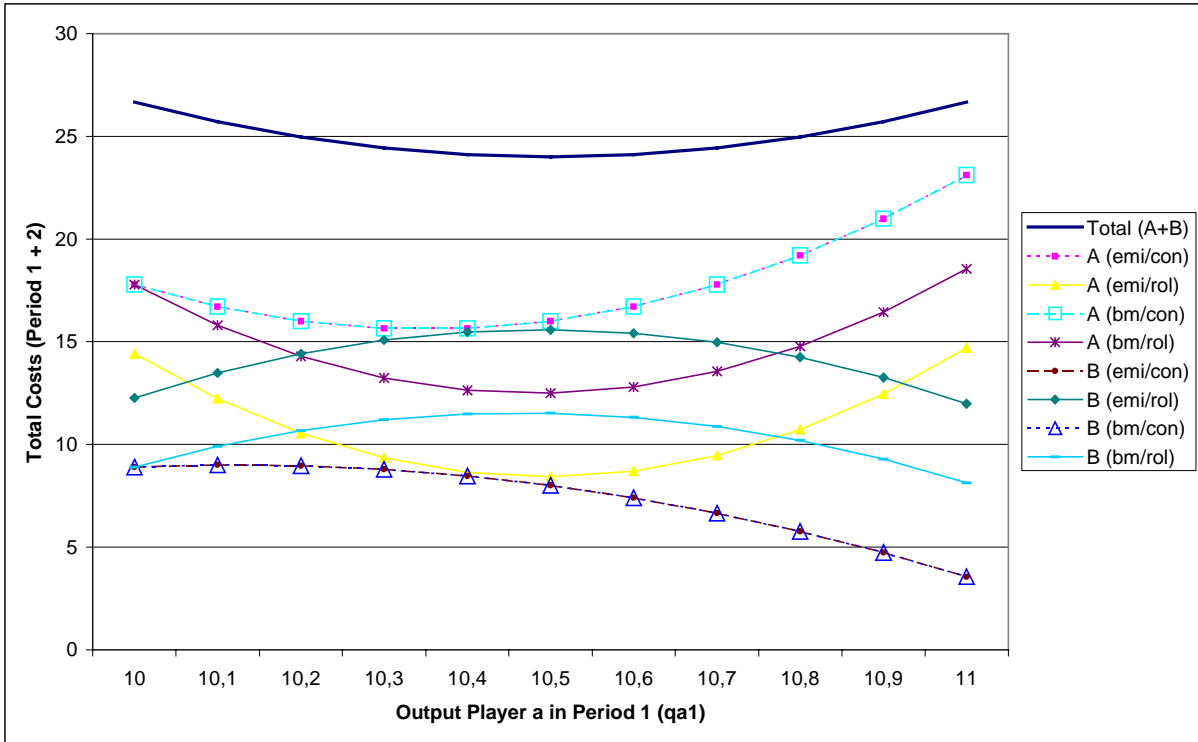


Fig. 2: Total cost over both periods with Player a changing output in the first period with reduction by end-of-pipe technology (all other parameters as given in Tab. 1, $q_{a2} = 20 - q_{a1}$; $q_{b1} = q_{b2} = 10$);
emi = emission based allocation, bm = benchmark based allocation, con = constant allocation, rol = rolling allocation.

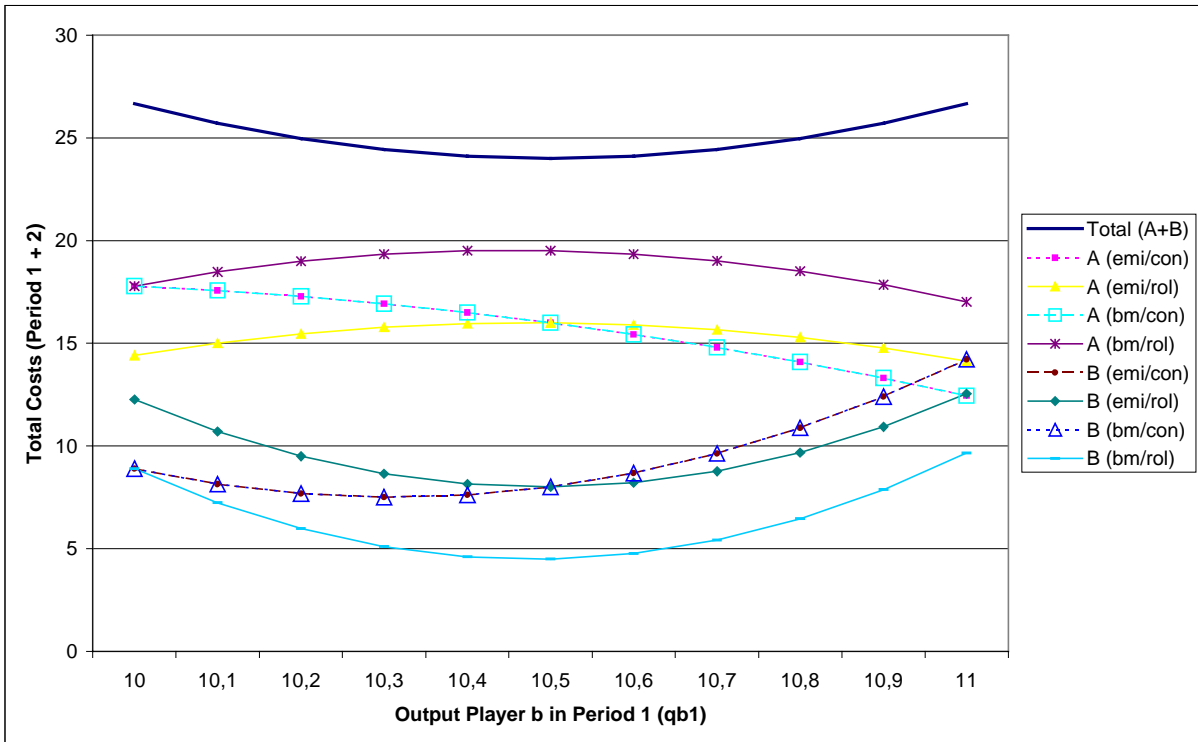


Fig. 3: Total cost over both periods with Player b changing output in the first period with reduction by end-of-pipe technology (all other parameters as given in Tab. 1, $q_{b2} = 20 - q_{b1}$; $q_{a1} = q_{a2} = 10$)

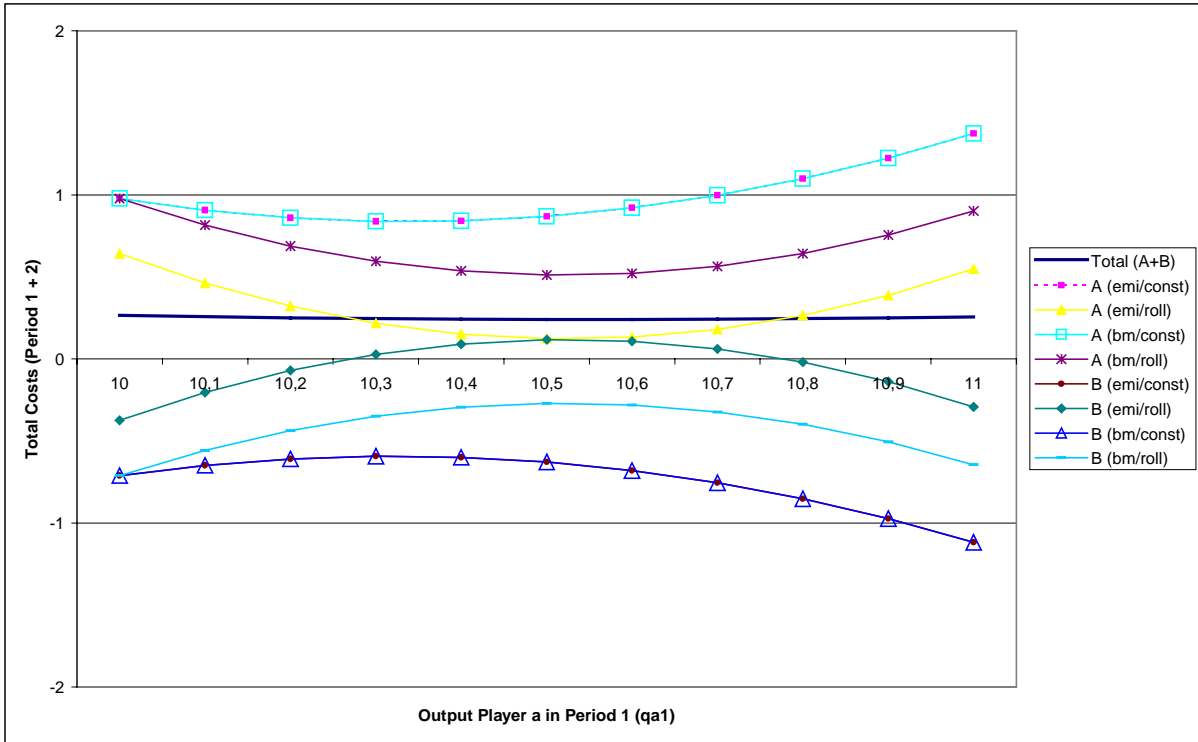


Fig. 4: Total cost over both periods with Player a changing output in the first period with reductions by improvement of emission intensity (all other parameters as given in Tab. 1, $q_{a2} = 20 - q_{a1}$; $q_{b1} = q_{b2} = 10$)

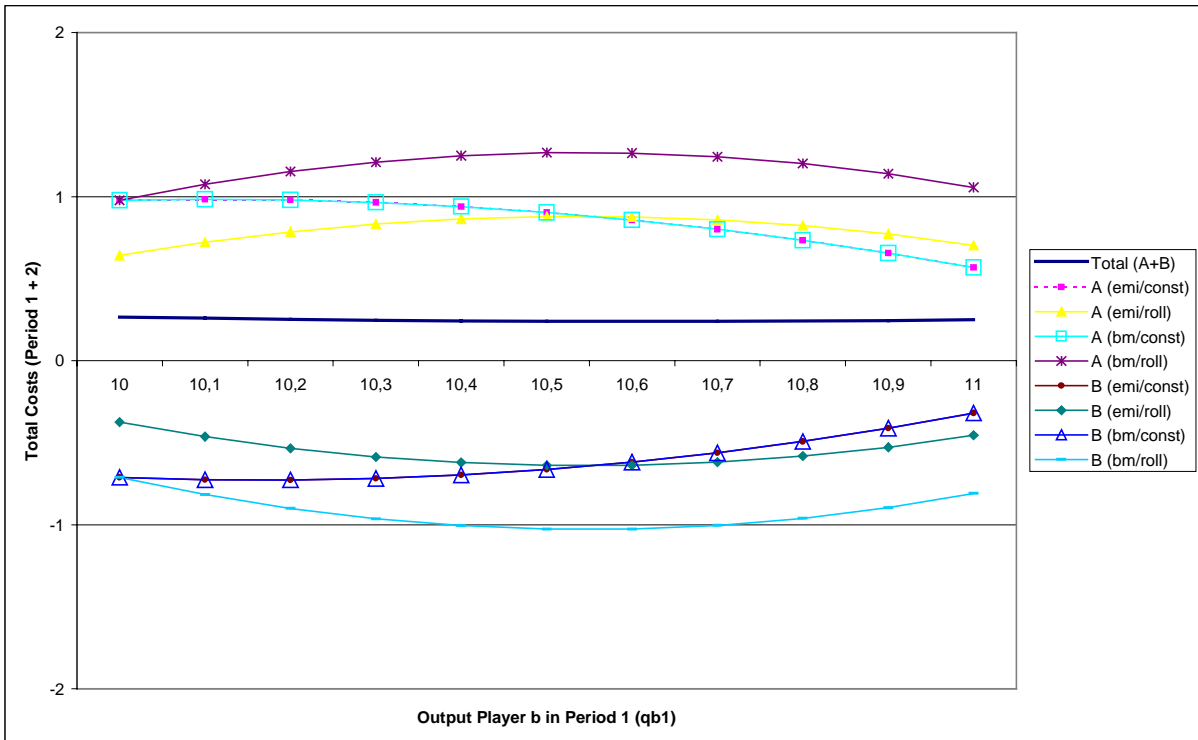


Fig. 5: Total cost over both periods with Player b changing output in the first period with reductions by improvement of emission intensity (all other parameters as given in Tab. 1, $q_{b2} = 20 - q_{b1}$; $q_{a1} = q_{a2} = 10$)

As can be seen in Fig. 2 to 5 both players can reduce their total costs over both periods by increasing production in the first period to a certain degree. Beyond this point, the benefits from a higher allocation in the second period are lost for higher compliance costs in the first one. With a *constant* allocation the costs are the same for both, emission-based and benchmark allocation. For a *rolling* allocation, however, the situation is different. Player *a* prefers the emission based approach for the range of output depicted in Fig. 2 and 4 (i.e. quantities around player *a*'s cost minimum).¹⁶ On the other hand player *b* prefers the benchmark. (I only discuss the point of view of the emitter who increases output.)

When asking for the preferences with regard to a rolling and a constant allocation we find that the player with the higher marginal abatement costs always prefers the former (regardless whether it is emission- or benchmark-based) whereas the seller's position depend on the output in period one. If one asks for the optimal quantity to produce in period one, it turns out that it is indeed dependent on the allocation method applied.

Furthermore, we can see that the total costs (a and b) also decrease to a certain level with increasing output in period one. This can be explained by the more stringent allocation in period two that makes emissions at that time more expensive.

As we have seen, both players have an incentive to increase output to a certain degree so that the question arises what happens in case they take their decision independently and both start to extend their production? Fig 6 and 7 show the impact on the costs with both players increasing output by the same amount.

¹⁶ For a very large increase of output this changes and he prefers the benchmark. Obviously, with small increases the fact that he reduces less emissions due to his higher abatement costs and the resulting increased allocation in the second period is dominating. With large increases of output this effect is topped by the resulting bigger allocation with a benchmark approach.

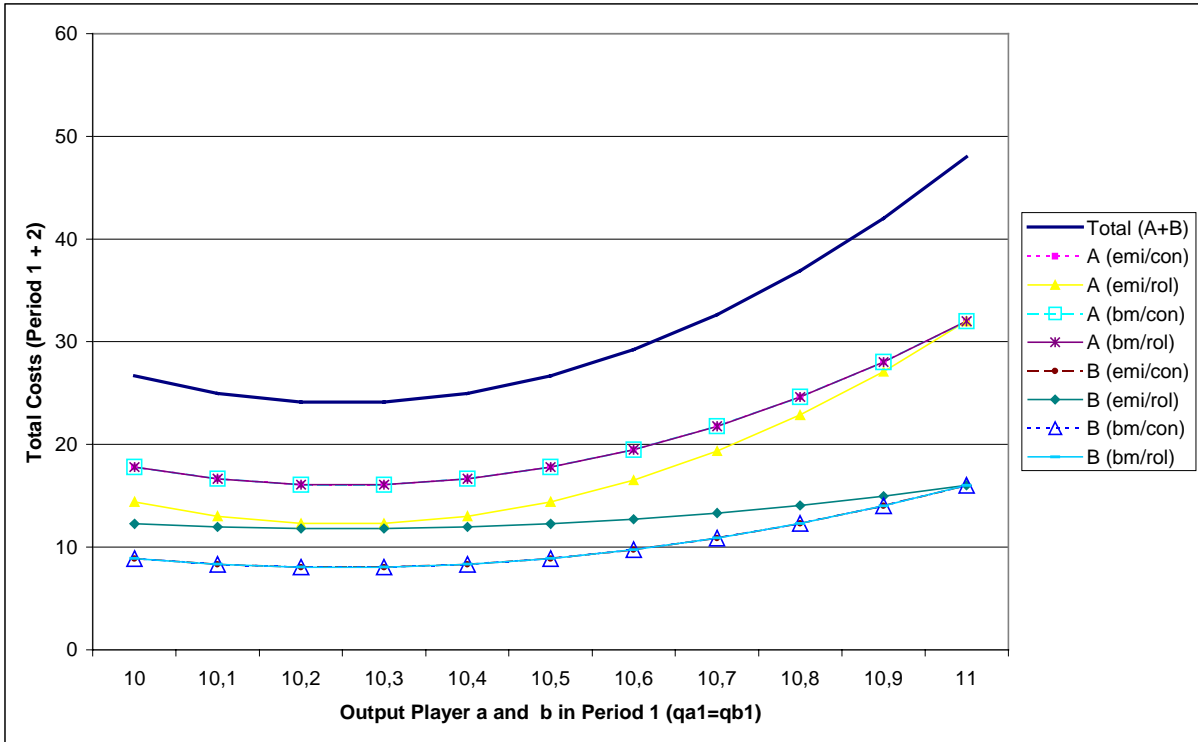


Fig. 6: Total cost over both periods with Player a and b changing output in the first period and with reductions by end-of-pipe technology (all other parameters as given in Tab. 1, $q_{a2} = q_{b2} = (40 - q_{a1} - q_{b1})/2$)

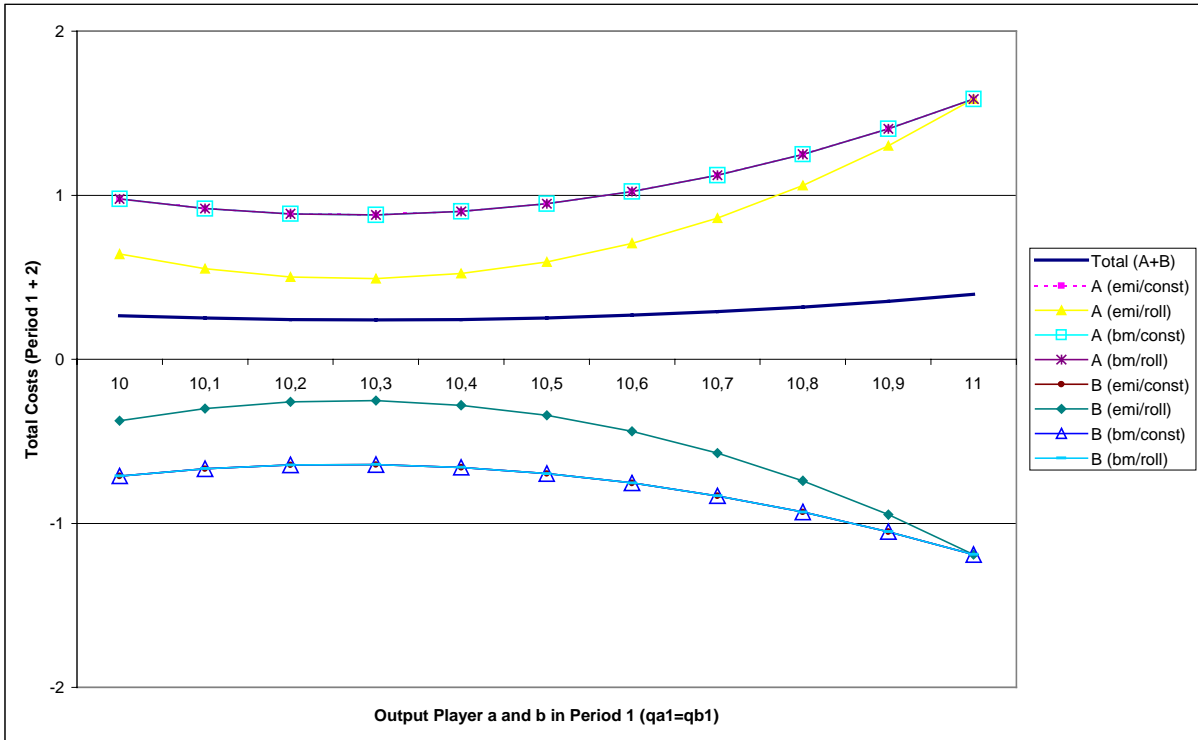


Fig. 7: Total cost over both periods with Player a and b changing output in the first period and with reductions by improvement of emission intensity (all other parameters as given in Tab. 1, $q_{a2} = q_{b2} = (40 - q_{a1} - q_{b1})/2$)

In Fig. 6 and Fig. 7 we see again the potential to lower the total costs over both periods by increasing (cumulative) output to some extent in the first period. We can also see that, if each player chooses the optimal quantity from his point of view (see Fig. 2 to 5), the cumulative output is bigger than the (total) cost minimising one. Interestingly, this benefits player *b* more than player *a*. A game theoretical analysis of this (interactive) decision problem is desirable. However, when discussing the findings presented in Fig 2 to 7 we have to keep in mind that the outcome is specific to the underlying model that is restricted to two periods only. It goes without saying that a reduced output in period two would have an impact on the allocation in period three and so on. An extended model in the ongoing analysis will take this into account.

5 Conclusion

GHG-Emission trading has become more and more important in the context of climate change in recent years. After trading on country level has been agreed in 1997 in the Kyoto-Protocol, it is currently under discussion on entity level. Before implementing any scheme a lot of design features have been decided on with the question on how to allocate the allowances being a very important one from the participants' point of view. The latter have argued for an allocation free of charge.

For this, I have analysed the implications of an allocation free of charge based on historical emissions and on benchmarks in multi-period emission trading. Different allocation methods in the successive periods have been studied in this paper using a two-player two-period model. I find that – even though all participants are likely to agree on an allocation free of charge – they have different preferences with regard to the allocation method over time. With equal emission intensities, the net-buying emitter prefers a rolling, emission-based allocation to any other option as the number of allowances received increases in the second period. Thus compliance costs are reduced. The net-seller on the other hand is likely to reject this option as it entails the highest compliance costs. With different emission intensities, preferences may change depending on the intensity. Furthermore, it turned out that a benchmark-based allocation that takes into account a total budget constraint as, for example, the Kyoto targets of Annex B countries, results in an individual allocation that is only depending on the emitters' share of the total output and that is thus not dependent on the individual emission intensities anymore. Consequently, there would be no need to try to determine any of such benchmark as it is currently done in the context of the upcoming EU directive on emissions trading.

The total costs for meeting the overall reduction target are, however, not affected by the individual allocation as emissions are reduced where abatement is cheapest. This would imply that national authorities developing a national allocation plan, could choose whatever option they like or simply allocate emission rights to those emitters “screaming loudest”.

Eventually, we found that seller and buyer have an incentive to increase output in the first period to a certain degree in order to get more allowances in the second one and thus to reduce total costs over both periods. If both player decide to do so individually, the total costs may become higher than the potential minimum.

All results are derived from the specific model and the assumptions made. Further analyses (the role of banking, of different life-times of the investments and game theoretic implications from the incentive to increase output in early periods) will be carried out. All errors are mine.

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7 Annex

Tab. A1: Impact of different allocation options over time with growing output for player a and reductions by end-of-pipe technology

Name	Symbol	Period 0			Period 1			Period 2 (emission based)			Period 2 (benchmark)		
		Constant	Rolling	Change	Constant	Rolling	Change	Constant	Rolling	Change	Constant	Rolling	Change
<i>Output</i>	/												
Output (a)	q_a	10	10,2	10,2	/	10,4	10,4	/	10,4	10,4	/		
Output (b)	q_b	10	10	10	/	10	10	/	10	10	/		
<i>Emissions</i>	/												
Emissions (a)	$I_a q_a$	20	19,60	19,60	0	19,20	19,20	0,00	19,20	19,20	0,00		
Emissions (b)	$I_b q_b$	20	18,40	18,40	0	16,80	16,80	0,00	16,80	16,80	0,00		
Total (a+b)	/	40	38,00	38,00	0	36,00	36,00	0,00	36,00	36,00	0,00		
<i>Allocation</i>													
Allocation (a)	A_a	/	19,00	19,00	0	18,35	18,57	0,22	18,00	18,18	0,18		
Allocation (b)	A_b	/	19,00	19,00	0	17,65	17,43	-0,22	18,00	17,82	-0,18		
<i>The Market</i>													
Allowance price	π	/	6,40	6,40	0	12,80	12,80	0,00	12,80	12,80	0,00		
Allowances traded	P	/	0,60	0,60	0	1,20	0,63	-0,57	1,20	1,02	-0,18		
Reductions (a)	R_a	/	0,80	0,80	0	1,60	1,60	0,00	1,60	1,60	0,00		
Reductions (b)	R_b	/	1,60	1,60	0	3,20	3,20	0,00	3,20	3,20	0,00		
<i>Costs (a)</i>	/												
Reductions	$\alpha_a R_a^2$	/	2,56	2,56	0	10,24	10,24	0,00	10,24	10,24	0,00		
Allowances	πP	/	3,84	3,84	0	15,36	8,08	-7,28	15,36	13,08	-2,28		
Total (a)	C_a	/	6,40	6,40	0	25,60	18,32	-7,28	25,60	23,32	-2,28		
<i>Costs (b)</i>	/												
Reductions	$\alpha_b R_b^2$	/	5,12	5,12	0	20,48	20,48	0,00	20,48	20,48	0,00		
Allowances	πP	/	-3,84	-3,84	0	-15,36	-8,08	7,28	-15,36	-13,08	2,28		
Total (b)	C_b	/	1,28	1,28	0	5,12	12,40	7,28	5,12	7,40	2,28		
Total (a+b)	/	/	7,68	7,68	0	30,72	30,72	0,00	30,72	30,72	0,00		

Tab. A2: Impact of different allocation options over time with growing output for player b and reductions by end-of-pipe technology

Name	Symbol	Period 0			Period 1			Period 2 (emission based)			Period 2 (benchmark)		
		Constant	Rolling	Change	Constant	Rolling	Change	Constant	Rolling	Change	Constant	Rolling	Change
<u>Output</u>	/												
Output (a)	q_a	10	10	10	/	10	10	/	10	10	/		
Output (b)	q_b	10	10,2	10,2	/	10,4	10,4	/	10,4	10,4	/		
<u>Emissions</u>	/												
Emissions (a)	$I_a q_a$	20	19,20	19,20	0	18,40	18,40	0,00	18,40	18,40	0,00		
Emissions (b)	$I_b q_b$	20	18,80	18,80	0	17,60	17,60	0,00	17,60	17,60	0,00		
Total (a+b)	/	40	38,00	38,00	0	36,00	36,00	0,00	36,00	36,00	0,00		
<u>Allocation</u>													
Allocation (a)	A_a	/	19,00	19,00	0	17,65	18,19	0,54	18,00	17,82	-0,18		
Allocation (b)	A_b	/	19,00	19,00	0	18,35	17,81	-0,54	18,00	18,18	0,18		
<u>The Market</u>													
Allowance price	π	/	6,40	6,40	0	12,80	12,80	0,00	12,80	12,80	0,00		
Allowances traded	P	/	0,20	0,20	0	0,40	0,21	-0,19	0,40	0,58	0,18		
Reductions (a)	R_a	/	0,80	0,80	0	1,60	1,60	0,00	1,60	1,60	0,00		
Reductions (b)	R_b	/	1,60	1,60	0	3,20	3,20	0,00	3,20	3,20	0,00		
<u>Costs (a)</u>	/												
Reductions	$\alpha_a R_a^2$	/	2,56	2,56	0	10,24	10,24	0,00	10,24	10,24	0,00		
Allowances	πP	/	1,28	1,28	0	5,12	2,69	-2,43	5,12	7,40	2,28		
Total (a)	C_a	/	3,84	3,84	0	15,36	12,93	-2,43	15,36	17,64	2,28		
<u>Costs (b)</u>	/												
Reductions	$\alpha_b R_b^2$	/	5,12	5,12	0	20,48	20,48	0,00	20,48	20,48	0,00		
Allowances	πP	/	-1,28	-1,28	0	-5,12	-2,69	2,43	-5,12	-7,40	-2,28		
Total (b)	C_b	/	3,84	3,84	0	15,36	17,79	2,43	15,36	13,08	-2,28		
Total (a+b)	/	/	7,68	7,68	0	30,72	30,72	0,00	30,72	30,72	0,00		

Tab. A3: Impact of different allocation options over time with constant output for both players and reductions by intensity improvement

Name	Symbol	Period 0		Period 1			Period 2 (emission based)			Period 2 (benchmark)		
		Constant	Rolling	Change	Constant	Rolling	Change	Constant	Rolling	Change		
<u>Output</u>												
Output (a)	q_a	10	10	10	/	10	10	/	10	10	/	
Output (b)	q_b	10	10	10	/	10	10	/	10	10	/	
<u>Emissions</u>												
Emissions (a)	$I_a q_a$	20	19,33	19,33	0,0	18,67	18,67	0,00	18,67	18,67	0,00	
Emissions (b)	$I_b q_b$	20	18,67	18,67	0,0	17,33	17,33	0,00	17,33	17,33	0,00	
Total (a+b)	/	40	38,00	38,00	0,0	36,00	36,00	0,00	36,00	36,00	0,00	
<u>Allocation</u>												
Allocation (a)	A_a	/	19,00	19,00	0	18,00	18,32	0,32	18,00	18,00	0,00	
Allocation (b)	A_b	/	19,00	19,00	0	18,00	17,68	-0,32	18,00	18,00	0,00	
<u>The Market</u>												
Allowance price	π	/	0,53	0,53	0	1,07	1,07	0,00	1,07	1,07	0,00	
Allowances traded	P	/	0,33	0,33	0	0,67	0,35	-0,32	0,67	0,67	0,00	
Reductions (a)	R_a	/	0,07	0,07	0	0,13	0,13	0,00	0,13	0,13	0,00	
Reductions (b)	R_b	/	0,13	0,13	0	0,27	0,27	0,00	0,27	0,27	0,00	
<u>Costs (a)</u>												
Reductions	$\alpha_a R_a^2$	/	0,02	0,02	0	0,07	0,07	0,00	0,07	0,07	0,00	
Allowances	πP	/	0,18	0,18	0	0,71	0,37	-0,34	0,71	0,71	0,00	
Total (a)	C_a	/	0,20	0,20	0	0,78	0,45	-0,34	0,78	0,78	0,00	
<u>Costs (b)</u>												
Reductions	$\alpha_b R_b^2$	/	0,04	0,04	0	0,14	0,14	0,00	0,14	0,14	0,00	
Allowances	πP	/	-0,18	-0,18	0	-0,71	-0,37	0,34	-0,71	-0,71	0,00	
Total (b)	C_b	/	-0,14	-0,14	0	-0,57	-0,23	0,34	-0,57	-0,57	0,00	
Total (a+b)	/	/	0,05	0,05	0	0,21	0,21	0,00	0,21	0,21	0,00	

Tab. A4: Impact of different allocation options over time with growing output for player a and reductions by intensity improvement

Name	Symbol	Period 0		Period 1			Period 2 (emission based)			Period 2 (benchmark)		
		Constant	Rolling	Change	Constant	Rolling	Change	Constant	Rolling	Change		
<u>Output</u>												
Output (a)	q_a	10	10,2	10,2	/	10,4	10,4	/	10,4	10,4	/	
Output (b)	q_b	10	10	10	/	10	10	/	10	10	/	
<u>Emissions</u>												
Emissions (a)	$I_a q_a$	20	19,59	19,59	0,0	19,16	19,16	0,00	19,16	19,16	0,00	
Emissions (b)	$I_b q_b$	20	18,41	18,41	0,0	16,84	16,84	0,00	16,84	16,84	0,00	
Total (a+b)	/	40	38,00	38,00	0,0	36,00	36,00	0,00	36,00	36,00	0,00	
<u>Allocation</u>												
Allocation (a)	A_a	/	19,00	19,00	0	18,00	18,56	0,56	18,00	18,18	0,18	
Allocation (b)	A_b	/	19,00	19,00	0	18,00	17,44	-0,56	18,00	17,82	-0,18	
<u>The Market</u>												
Allowance price	π	/	0,64	0,64	0	1,26	1,26	0,00	1,26	1,26	0,00	
Allowances traded	P	/	0,59	0,59	0	1,16	0,60	-0,56	1,16	0,98	-0,18	
Reductions (a)	R_a	/	0,08	0,08	0	0,16	0,16	0,00	0,16	0,16	0,00	
Reductions (b)	R_b	/	0,16	0,16	0	0,32	0,32	0,00	0,32	0,32	0,00	
<u>Costs (a)</u>												
Reductions	$\alpha_a R_a^2$	/	0,03	0,03	0	0,10	0,10	0,00	0,10	0,10	0,00	
Allowances	πP	/	0,37	0,37	0	1,46	0,76	-0,71	1,46	1,24	-0,23	
Total (a)	C_a	/	0,40	0,40	0	1,56	0,86	-0,71	1,56	1,34	-0,23	
<u>Costs (b)</u>												
Reductions	$\alpha_b R_b^2$	/	0,05	0,05	0	0,20	0,20	0,00	0,20	0,20	0,00	
Allowances	πP	/	-0,37	-0,37	0	-1,46	-0,76	0,71	-1,46	-1,24	0,23	
Total (b)	C_b	/	-0,32	-0,32	0	-1,26	-0,56	0,71	-1,26	-1,04	0,23	
Total (a+b)	/	/	0,08	0,08	0	0,30	0,30	0,00	0,30	0,30	0,00	

Tab. A5: Impact of different allocation options over time with growing output for player b and reductions by intensity improvement

Name	Symbol	Period 0	Period 1			Period 2 (emission based)			Period 2 (benchmark)		
		Constant	Rolling	Change	Constant	Rolling	Change	Constant	Rolling	Change	
<u>Output</u>											
Output (a)	q_a	10	10	10	/	10	10	/	10	10	/
Output (b)	q_b	10	10,2	10,2	/	10,4	10,4	/	10,4	10,4	/
<u>Emissions</u>											
Emissions (a)	$I_a q_a$	20	19,21	19,21	0,0	18,44	18,44	0,00	18,44	18,44	0,00
Emissions (b)	$I_b q_b$	20	18,79	18,79	0,0	17,56	17,56	0,00	17,56	17,56	0,00
Total (a+b)	/	40	38,00	38,00	0,0	36,00	36,00	0,00	36,00	36,00	0,00
<u>Allocation</u>											
Allocation (a)	A_a	/	19,00	19,00	0	18,00	18,20	0,20	18,00	17,82	-0,18
Allocation (b)	A_b	/	19,00	19,00	0	18,00	17,80	-0,20	18,00	18,18	0,18
<u>The Market</u>											
Allowance price	π	/	0,63	0,63	0	1,25	1,25	0,00	1,25	1,25	0,00
Allowances traded	P	/	0,21	0,21	0	0,44	0,24	-0,20	0,44	0,62	0,18
Reductions (a)	R_a	/	0,08	0,08	0	0,16	0,16	0,00	0,16	0,16	0,00
Reductions (b)	R_b	/	0,16	0,16	0	0,31	0,31	0,00	0,31	0,31	0,00
<u>Costs (a)</u>											
Reductions	$\alpha_a R_a^2$	/	0,02	0,02	0	0,10	0,10	0,00	0,10	0,10	0,00
Allowances	πP	/	0,13	0,13	0	0,55	0,30	-0,25	0,55	0,77	0,22
Total (a)	C_a	/	0,16	0,16	0	0,65	0,40	-0,25	0,65	0,87	0,22
<u>Costs (b)</u>											
Reductions	$\alpha_b R_b^2$	/	0,05	0,05	0	0,19	0,19	0,00	0,19	0,19	0,00
Allowances	πP	/	-0,13	-0,13	0	-0,55	-0,30	0,25	-0,55	-0,77	-0,22
Total (b)	C_b	/	-0,08	-0,08	0	-0,36	-0,11	0,25	-0,36	-0,58	-0,22
Total (a+b)	/	/	0,07	0,07	0	0,29	0,29	0,00	0,29	0,29	0,00

Tab. A6: Compliance costs (both periods) with different initial emission intensity for player b with growing output for player a and reductions by end-of-pipe technology ^{*)}

Emission intensity player b ^{*)} (I _b)	Total (a+b)	Player a				Player b			
		emi/const	emi/rol	bm/const	bm/rol	emi/const	emi/rol	bm/const	bm/rol
2,1	60,27	46,90	36,21	40,11	37,36	13,36	24,06	20,15	22,91
2,2	87,47	64,20	49,81	48,66	45,43	23,26	37,66	38,81	42,04
2,3	120,00	83,61	65,37	57,49	53,78	36,39	54,63	62,51	66,22
2,4	157,87	104,86	82,76	66,46	62,27	53,01	75,11	91,41	95,59
2,5	201,07	127,70	101,85	75,44	70,78	73,36	99,22	125,63	130,29

^{*)} Other values for parameters as in Tab. 1, q_{a1} = 10,2; q_{a2} = 10,4; q_{b1} = q_{b2} = 10

Tab. A7: Compliance costs (both periods) with different initial emission intensity for player b with growing output for player b and reductions by end-of-pipe technology ^{*)}

Emission intensity player b ^{*)} (I _b)	Total (a+b)	Player a				Player b			
		emi/const	emi/rol	bm/const	Bm/rol	emi/const	emi/rol	bm/const	bm/rol
2,1	61,07	30,97	26,20	24,14	26,91	30,10	34,87	36,93	34,16
2,2	89,40	45,17	37,79	29,45	32,72	44,23	51,61	59,95	56,68
2,3	123,38	61,50	51,38	34,97	38,74	61,89	72,00	88,41	84,65
2,4	163,03	79,67	66,83	40,57	44,83	83,36	96,20	122,46	118,20
2,5	208,33	99,44	84,01	46,11	50,86	108,89	124,33	162,22	157,47

^{*)} Other values for parameters as in Tab. 1, q_{b1} = 10,2; q_{b2} = 10,4; q_{a1} = q_{a2} = 10

Tab. A8: Compliance costs (both periods) with different initial emission intensity for player b with constant output and reductions by intensity improvement ^{*)}

Emission intensity player b ^{*)} (I _b)	Total (a+b)	Player a				Player b			
		emi/const	emi/rol	bm/const	Bm/rol	emi/const	emi/rol	bm/const	bm/rol
2,1	0,45	1,55	0,97	0,97	0,97	-1,10	-0,51	-0,51	-0,51
2,2	0,69	2,21	1,35	0,84	0,84	-1,52	-0,65	-0,15	-0,15
2,3	0,99	2,93	1,76	0,59	0,59	-1,94	-0,78	0,40	0,40
2,4	1,33	3,68	2,21	0,19	0,19	-2,34	-0,87	1,15	1,15
2,5	1,73	4,43	2,66	-0,37	-0,37	-2,70	-0,93	2,10	2,10

^{*)} Other values for parameters as in Tab. 1, q_{a1} = q_{b1} = q_{a2} = q_{b2} = 10

Tab. A9: Compliance costs (both periods) with different initial emission intensity for player b with growing output for player a and reductions by intensity improvement ^{*)}

Emission intensity player b ^{*)} (I _b)	Total (a+b)	Player a				Player b			
		emi/const	emi/rol	bm/const	bm/rol	emi/const	emi/rol	bm/const	bm/rol
2,1	0,59	2,76	1,72	2,09	1,81	-2,17	-1,13	-1,50	-1,22
2,2	0,86	3,62	2,23	2,09	1,77	-2,77	-1,38	-1,23	-0,91
2,3	1,17	4,53	2,78	1,95	1,59	-3,36	-1,60	-0,78	-0,41
2,4	1,54	5,45	3,34	1,66	1,25	-3,91	-1,79	-0,12	0,29
2,5	1,97	6,37	3,90	1,21	0,75	-4,40	-1,93	0,75	1,21

*) Other values for parameters as in Tab. 1, $q_{a1} = 10,2$; $q_{a2} = 10,4$; $q_{b1} = q_{b2} = 10$

Tab. A10: Compliance costs (both periods) with different initial emission intensity for player b with growing output for player b and reductions by intensity improvement *)

Emission intensity player b *) (I_b)	Total (a+b)	Player a				Player b			
		emi/const	emi/rol	bm/const	bm/rol	emi/const	emi/rol	bm/const	bm/rol
2,1	0,58	1,32	0,84	0,66	0,93	-0,74	-0,25	-0,07	-0,34
2,2	0,85	1,92	1,17	0,39	0,70	-1,06	-0,31	0,47	0,15
2,3	1,18	2,56	1,53	-0,02	0,35	-1,38	-0,35	1,20	0,84
2,4	1,56	3,23	1,92	-0,58	-0,16	-1,67	-0,35	2,14	1,73
2,5	2,00	3,89	2,31	-1,30	-0,84	-1,90	-0,31	3,30	2,83

*) Other values for parameters as in Tab. 1, $q_{b1} = 10,2$; $q_{b2} = 10,4$; $q_{a1} = q_{a2} = 10$