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Revisiting the case for intensity targets: Better incentives and less uncertainty for developing countries

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ABSTRACT

In the debate on post-Kyoto global climate policy, intensity targets, which set a maximum amount of emissions per GDP, figure as prominent alternative to Kyoto-style absolute emission targets, especially for developing countries. This paper re-examines the case for intensity targets by critically assessing several of its properties, namely (i) reduction of cost-uncertainty, (ii) reduction of 'hot air', (iii) compatibility with international emissions trading, (iv) incentive to decouple carbon emissions and economic output (decarbonization), and, (v) use as a substitute for banking/borrowing. Relying on simple analytical models, it is shown that the effect on cost-uncertainty is ambiguous and depends on parameter values, and that the same holds for the risk of 'hot air'; that the intensity target distorts international emissions trading; that despite potential asymmetries in the choice of abatement technology between absolute and intensity target, the incentive for a lasting transformation of the energy system is not necessarily stronger under the latter; and, finally, that only a well-working intensity target could substitute banking/borrowing to some extent—but also vice versa. Overall, the results suggest that due to the increased complexity and the potentially only modest benefits of an intensity target, absolute targets remain a robust choice for a cautious policy maker.

1. Introduction

What kind of follow-up agreement should or could succeed the United Nation's Kyoto Protocol, due to expire in 2012, is currently the central question in international climate policy (e.g. Aldy and Stavins, 2007; Aldy and Stavins, 2009). Among the various issues, one aspect regards the mechanism by which emission control is to be implemented. On the one hand there are *absolute* targets, which require future emissions not to exceed a certain amount of CO_2 (or CO_2 equivalents). Such targets, also referred to as caps, were adopted by most industrialized countries under the Kyoto Protocol. On the other hand, the so-called *intensity* targets[1] set an upper limit on the ratio of emissions to output, expressed in CO_2 per GDP. As a prominent example, the U.S. administration announced such a target in 2002, pledging to reduce greenhouse gas emissions relative to GDP by 18% over a ten year period.[2] Recently, the approach received a boost when Canada (Government of Canada, 2007) and China[3] expressed their intention to implement intensity targets in the coming years. It was also suggested to devise such targets only for some sectors of major developing economies, in order for them to participate in international permit trade (Schmidt et al., 2006).

The strong emphasis on mechanisms capable to facilitate the participation of developing countries in climate change mitigation (Kim and Baumert, 2002) reflects the insight that without their contribution, avoiding dangerous climate change will hardly be feasible and – in any case – definitely not cost-effective. However, developing countries have so far remained hesitant, fearing that any type of binding emission restriction would be in conflict with their development objectives.

Against this backdrop, intensity targets have been characterized as a more acceptable type of commitment for developing countries, as they can "alleviate developing countries' concerns about constraining their development" (Philibert and Pershing, 2001) by reducing cost-uncertainty and offering a way to contribute to international mitigation efforts while retaining some scope for emissions growth, which – in face of their growth ambitions – seems unavoidable in the near term (Pizer, 2005). By creating the right type of incentive, they would foster "clean growth" and help to put development countries on "low-emissions pathways" (Herzog et al., 2006). Moreover, they are

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[1] Also called dynamic (e.g. IEA, 2003) or indexed (e.g. Newell and Pizer, 2008) targets.

[2] See White House news release 2002/02 on climate change.

[3] See, e.g. the speech of President Hu at the UN general assembly on 22 September 2009.

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expected to alleviate 'hot air' (Philibert and Pershing, 2001) and may readily be integrated in international emissions trading (IEA, 2003).[4]

However, few of these prospective benefits of the intensity target have undergone formal analysis, and if so – as in the case of uncertainty reduction (e.g. Sue Wing et al., 2009) – not within a comprehensive assessment that compares and weighs the results for all the different aspects. It is this gap that the present contribution wants to address, by presenting a formal assessment of five potential merits of the intensity target.

First, the question of cost-uncertainty is briefly revisited, showing that whether or not an intensity target leads to less uncertainty than a cap depends on (potentially uncertain) parameter values. Second, a short analysis yields the result that the same also holds with respect to the reduction of 'hot air'. Third, emissions trading between a country with absolute and one with intensity target is investigated, demonstrating that this leads to inefficient allocations and to an expansion of global emissions whenever the country with intensity target is a net importer of permits. Fourth, the hypothesis that an intensity target creates a stronger incentive for a systematic decarbonization of the energy system is assessed. By means of an exemplary analysis of abatement through intensity reduction versus end-of-pipe abatement (interpretable as carbon capturing and sequestration), it is shown that the incentive to reduce emission intensity is not necessarily weaker under an absolute cap. Fifth, the question of whether an intensity target could act as a substitute for a banking/borrowing mechanism is explored. It results to be the case only to a limited extent, i.e. an absolute cap with banking/borrowing will likely constitute a better way for reducing the fluctuation of abatement over time. In conclusion it is argued that absolute caps represent the more robust policy choice, given the doubts or at least uncertainties on several issues about the effective benefits of an intensity target.

The remaining part of the paper is organized as follows: the next section reviews related literature on the subject. Section 3 defines the two types of targets. Section 4 addresses cost-uncertainty, Section 5 'hot air'. Section 6 discusses the efficiency of emissions trading, and Section 7 the incentives for decarbonization. Section 8 analyzes banking/borrowing, and Section 9 concludes.

2. Related literature

The early literature dealt with the basic properties of the intensity target and highlighted its potential to reduce cost-uncertainty, using both qualitative (Frankel, 1999; Philibert and Pershing, 2001, IEA, 2003) and quantitative approaches based on the (exemplary) use of GDP and emissions data (Kim and Baumert, 2002). More formal analytical treatments of the question of uncertainty were offered by Kolstad (2005) and Ellerman and Sue Wing (2003): starting from slightly different assumptions on the link between GDP, emissions, and abatement costs, the former shows intensity targets to always reduce uncertainty, while the latter find that they are superior only if "generalized growth-indexed" targets are employed, which allow to tie emissions to GDP with an elasticity of less than unity. Following up on this, Sue Wing et al. (2009) present a comprehensive formal analysis of the abatement uncertainty (taken as proxy for cost-uncertainty) under absolute and intensity target, establishing the formal condition to be discussed later in Section 4. Although they also included a formal comparison of "temporal stability" of abatement under the two types of targets, they did not, however, extend the analysis to cover banking and borrowing.

The possibility that – due to reduced cost-uncertainty – intensity targets could offer a more acceptable type of commitment for developing countries was emphasized, among others, by Frankel (1999), Philibert and Pershing (2001), and Lisowski (2002). This conclusion is shared by Pizer (2005), but for slightly different reasons, namely on the grounds that intensity targets offer a better way of framing mitigation policy when absolute emission levels of developing countries are destined to rise, at least in the near term.

A different strand of literature follows the tradition of Weitzman's (1974) analysis of price versus quantity regulation, and includes the benefits of abatement in order to evaluate the general welfare implications of the intensity target. Based on an analytical approach, Quirion (2005) finds that in most cases either an emission tax or an absolute cap is preferred to the intensity target, but that in climate change policy the latter could be a second-best solution if the first-best, an emission tax, cannot be implemented for political reasons. This result is in essence confirmed and further elaborated by Newell and Pizer (2008), who confront their findings with empirical data to show that indeed indexed quantities would be second-best for about half of the considered countries.

The welfare implications of the intensity target were also assessed within empirically calibrated model simulations. In an 18-region global cap-and-trade model, Jotzo and Pezzey (2007) find that standard intensity targets have an overall positive impact, but not for every single country, since GDP-induced shocks on emissions tend to be "systematically over- or under-compensated". Tian and Whalley (2009) use a multi-regional model with a 30 and 50 years horizon with explicit disutility from rising global temperatures. By constructing plausible cases in which all countries prefer absolute over intensity targets, they illustrate that the ranking of targets is significantly influenced by model assumptions, in their case in particular on how growth rate uncertainty is specified.

Overall, the existing literature shows a focus on the intensity target's performance under uncertainty, be it in terms of expected abatement costs or net benefits. An exception with relevance for the present contribution is Fischer (2003): motivated by a similar question as the one addressed in Section 6, she examines trade of emission permits between a cap-and-trade and tradable performance standard program. However, despite a certain resemblance, the latter is actually different from an intensity target, as it is defined not at the national but sectoral level, and sets a limit on emissions per unit of physical output. Accordingly, her analysis adopts a micro-view and explicitly models the behavior of competitive firms in two sectors. Partially in line with the findings of Section 6, she finds that in the absence of cross-price effects permit trade always leads to an expansion of combined emissions, but then goes on to concentrate on the identification of suitable countermeasures.

3. Definition of intensity and absolute target

Consider a closed economy, and let Y be future economic output and E future emissions. Throughout the paper, a subscript zero is used for denoting the deterministic value of variables, i.e. the value they would take on in the absence of uncertainty. For symmetric uncertainty distributions, the expected (or mean) value coincides with the deterministic value: $\langle Y \rangle = Y_0$ and

[4] An often-mentioned drawback of the intensity target consists of its reduced environmental effectiveness, i.e. its outcome in terms of emission control is uncertain. However, over multiple time periods this uncertainty should average out (Jotzo and Pezzey, 2007).

$\langle E\rangle = E_0$. Finally, let γ be defined as the emission intensity of output E/Y, which in the absence of uncertainty is given by $\gamma_0 = E_0/Y_0$.

Two types of emission reductions will be considered: absolute targets (in short also 'caps'), which constrain emissions to a given level $\overline{E}$, and intensity targets, which set a maximum intensity of $\overline{\gamma}$. In a deterministic setting, absolute and intensity targets are equivalent instruments for the purpose of emission control, since any absolute target can be implemented through an intensity target (Ellerman and Sue Wing, 2003), where $\overline{\gamma} = \overline{E}/Y_0$ denotes what shall be called the equivalent intensity target.

4. Reduction of cost-uncertainty

In the literature, advocates of the intensity target argue that it reduces cost-uncertainty in the face of unknown – but GDP sensitive – business-as-usual emissions (Frankel, 1999; Kolstad, 2005; Strachan, 2007). In fact, when a country accepts an emission target, the incurred costs are uncertain for two reasons: first, in the face of unknown future baseline emissions the amount of abatement needed for meeting the target is uncertain; and, second, because of marginal abatement cost (MAC) uncertainty, i.e. the a priori unknown costs for reducing emissions by a given amount. Nevertheless, in what follows we abstract from MAC uncertainty, assuming that it would affect both types of targets equally, and hence that differences in cost-uncertainty are essentially driven by differences in the uncertainty about the required amount of abatement.

In formal terms, the overall reduction burden is given by the difference between baseline emissions E and the emissions target T (be it absolute or relative), and will be denoted by R. The associated level of uncertainty, expressed in terms of the variance σ_R^2, is given by[5]

$$\sigma_R^2 = \langle (E-T)^2\rangle - \langle (E-T)\rangle^2 = \sigma_E^2 - 2(\langle ET\rangle - \langle E\rangle\langle T\rangle) + \sigma_T^2. \quad (1)$$

For an absolute target, T becomes a fixed emission level $\overline{E}$, meaning that all terms except the first one cancel out, leaving only the uncertainty about future baseline emissions

$$\sigma_{R\_Cap}^2 = \sigma_E^2 \quad (2)$$

For an intensity target, T is given by the fixed emission intensity $\overline{\gamma}$ multiplied by economic output Y. The associated reduction uncertainty now becomes a function of the coefficient of correlation ρ, which captures the relationship between shocks in baseline emissions and output with respect to their expected values

$$\sigma_{R\_Int}^2 = \sigma_E^2 - 2\overline{\gamma}\sigma_E\sigma_Y\rho + \overline{\gamma}^2\sigma_Y^2 = \sigma_E^2\left(1 - \overline{\gamma}\frac{\sigma_Y}{\sigma_E}\left(2\rho - \overline{\gamma}\frac{\sigma_Y}{\sigma_E}\right)\right) \quad (3)$$

Comparison with Eq. (2) directly leads to the previously noted result that the intensity target reduces uncertainty only if the correlation ρ is higher than a parameter-dependent threshold value ρ_{min} (Sue Wing et al., 2009; Jotzo and Pezzey (2007))

$$\sigma_{R\_Int} < \sigma_{R\_Cap} \Leftrightarrow \rho > \frac{1}{2}\frac{\overline{\gamma}}{(E_0/Y_0)}\frac{\sigma_Y/Y_0}{\sigma_E/E_0} =: \rho_{\min} \quad (4)$$

It is intuitive that the intensity target does not always reduce uncertainty: if the uncertainty about future GDP is much higher than the uncertainty about future emissions, then a coupling of the target to GDP will introduce more new uncertainty than can be reduced.

The fraction $(\sigma_Y/Y_0)/(\sigma_E/E_0)$ in Eq. (4) can be interpreted as the ratio of the average (normalized) forecast errors for GDP and emissions, which has been estimated to be roughly around one (Marschinski and Lecocq, 2006). The other term is the ratio between target and BAU emission intensity—generally a value between zero and one. Thus, the equation implies that a significant positive correlation between shocks in E and Y is necessary in order for the intensity target to reduce cost uncertainty, and that a simple rule of thumb could be given by $\rho > 0.5$ (see also Höhne and Harnisch, 2002).[6]

This condition might not appear very demanding at first sight, given that the raw series of E and Y are indeed often strongly correlated (Peterson, 2008). However, it should be checked carefully, since the deviations from expected values (shocks, or forecast errors) do not always seem to be highly correlated, or, at a minimum, are difficult to estimate with high confidence. For instance, Newell and Pizer (2006, 2008) employ a vector forecasting model to compute ρ for 19 high-emitting countries, and find a wide range of values between 0.01 and 0.74, broadly in line with similar results reported by Marschinski and Lecocq (2006). Relatively low values for ρ seem plausible if, e.g. agriculture plays a strong role in a country's economy, or when electricity production is dominated by nuclear energy, as in France. Intuitively, shocks in emissions can also be related to non-economic factors, such as weather conditions, e.g. when a series of years with particularly cold winters causes higher energy consumption. However, a robust estimation of ρ is difficult not only because of data limitations, but also due to non-stationarity, i.e. structural changes occurring when countries pass from one stage of development to another (Höhne and Harnisch, 2002; Peterson, 2008).

As a short illustration, let us consider the hypothetical case of what would have happened if in the year 2000 China, India, and Russia had adopted a business-as-usual CO_2 target for 2010, and compare the outcome for an absolute and intensity target. To do so, we let the 2010 forecast of the 1999 International Energy Outlook (EIA, 1999) define the BAU target, which is then confronted with actual values.[7] As Table 1 shows, for China both emissions and GDP were grossly underestimated, which would have resulted in an unexpected reduction burden of more than $2GtCO_2$ under an absolute target, whereas the originally intended reduction – namely zero – would have been preserved almost perfectly under an intensity target. This is, of course, due to the fact that the forecast errors for CO_2 and GDP are nearly equal for China. However, the figures for India illustrate that this not always so: while GDP was also underestimated, India's emissions were in fact overestimated. The case is similar for Russia, where both were underestimated, but GDP much more than emissions. As a consequence, India and Russia would be facing a small amount of 'hot air' and a modest reduction requirement, respectively, under an absolute target, while they would have received massive amounts of 'hot air' in case of an intensity target. Although 'hot air' might not be perceived as bad as a high unexpected reduction burden, this – admittedly exemplary – illustration shows how the

[5] Note that uncertainty is represented solely through the second moment, i.e. the standard deviation, which is equivalent to assuming the underlying distribution to be normal.

[6] It is a conventional assumption to let the cost function depend on the nominal amount of abatement. However, though seemingly appropriate for end-of-pipe abatement such as CCS, where high variable costs dominate, it seems less justifiable for other abatement options. For example, when switching to natural gas or nuclear power, upfront fixed costs make up a significant part, and the achieved abatement will also depend on energy consumption, and thus be related to (uncertain) output. For such abatement options, modeling costs as a function of the percentage reduction with respect to BAU might be preferable. In this case, the minimal ρ from Eq. (4) turns out to be higher, as it becomes multiplied by the inverse target intensity. In reality, the cost function probably depends on both the nominal and relative percentage reduction.

[7] For lack of data proxied by the 2010 forecast of the current 2009 issue (EIA, 2009).

Table 1
Implications of a hypothetical business-as-usual target for the year 2010.

Country	1999 IEO forecast error for 2010		Implied reduction in 2010 under BAU target			
	CO_2 %	GDP %	Absolute cap		Intensity	
			(Mio tCO_2)	% Reduction	(Mio tCO_2)	% Reduction
China	−29	−30	2122	29	−62	−1
India	4	−21	−49	−4	−433	−32
Russia	−10	−42	187	10	−1000	−55

intensity target does not lead to the hoped-for results when forecast errors are not well-correlated.

In fact, under such conditions the costs of being wrong could be quite high: the variance may easily double when an intensity target is adopted although the actual value of ρ is approximately zero, as shown by Eq. (3). Severe consequences can ensue, e.g. when a country with intensity target suffers from an economic downturn and there is no accompanying drop in emissions; in the face of such a double burden non-compliance could become the preferred option for the country, possibly leading to a destabilization of the entire system. On the other side, the same equation implies that even in the most favorable cases (in terms of parameter values for γ, σ_E, and σ_Y), the reduction of uncertainty is bounded by $\sqrt{1-\rho^2}$, meaning that correlations of 1/2, 3/5, and 3/4 allow *at best* to reduce uncertainty by 13%, 20%, and 34%, respectively.

5. Reduction of ‘hot air’

Another benefit claimed for the intensity target is its presumed ability to reduce the incidence of ‘hot air’ (Philibert and Pershing, 2001), i.e. the unintended over-allocation occurring when a country’s baseline emissions turn out to be lower than its target. The undesirable effect of ‘hot air’ is that it allows selling permits that are not backed by actual abatement.[8] As the following formal analysis shows, the intensity target’s capacity to reduce the likelihood of ‘hot air’ is again contingent on parameter values; namely, the linear correlation ρ between GDP and emission shocks has to be high enough to satisfy Eq. (4), the condition which determined whether or not the intensity target lowers reduction uncertainty.[9]

The likelihood for a given emission target T to lead to a ‘hot air’ allocation is equal to the probability of the uncertain variable E to stay below T. Suppose future emissions E can be represented as $E=E_0+\varepsilon$, with ε as zero-mean stochastic error term. For an absolute cap $\overline{E}$, the probability of hot air occurrence can then be expressed as

$$\mathrm{Prob}[E<T]=\mathrm{Prob}[\varepsilon<\overline{E}-\langle E\rangle]=\mathrm{Prob}[\varepsilon<-R_0], \tag{5}$$

which corresponds to the cumulative distribution function of ε, evaluated at the negative expected reduction amount, $-R_0$. For instance, in case of a BAU level target ($\langle R\rangle=R_0=0$) the likelihood of ‘hot air’ amounts to 50%. In general, when ε is given by a normal distribution with standard deviation σ_E, the last expression is equal (up to normalization) to the error function.

For an intensity target, on the other side, the probability of ‘hot air’ occurrence is given by

$$\mathrm{Prob}[E<\overline{\gamma}Y]=\mathrm{Prob}[\varepsilon<\overline{\gamma}\langle Y\rangle+\overline{\gamma}\eta-\langle E\rangle]=\mathrm{Prob}[\varepsilon-\overline{\gamma}\eta<-R_0], \tag{6}$$

where future economic output Y is represented as a random variable in the same manner as emissions. In contrast to the absolute target, the probability now depends on the cumulative distribution of the convolution of ε and $\overline{\gamma}\eta$. If ε and η are characterized by a linear correlation ρ, then the term $\varepsilon-\overline{\gamma}\eta$ is again distributed normally, with zero mean and variance $\sigma_E^2+\overline{\gamma}^2\,\sigma_Y^2-2\overline{\gamma}\,\sigma_E\sigma_Y\rho$.

For negative arguments (i.e. a positive $\langle R\rangle$, corresponding to a target below BAU) the cumulative distribution of a zero mean normal is an increasing function of the variance. Thus, the probability of ‘hot air’ is larger for the target that exhibits higher variance. As in the case of reduction uncertainty, the expression for the intensity target Eq. (3) is smaller than the corresponding variance σ_E^2 of the absolute target if the condition in Eq. (4) is met.[10]

6. Compatibility with international emissions trading

Parallel to the negotiations on a follow-up agreement to the Kyoto Protocol, a number of national and regional emissions trading systems, e.g. in Europe, US, and New Zealand, have been installed or are currently emerging (Flachsland et al., 2008). Although absolute targets prevail, some systems contemplate the adoption of intensity targets (Government of Canada, 2007; Schmidt et al., 2006). As a consequence, a fragmented regime with one group of countries adopting the former and another group of countries the latter could become reality. The question then arises whether it is generally true that “emissions trading may also be easily accommodated within a dynamic target regime” (IEA, 2003). In other words, does emissions trading between countries that are not subject to the same type of emissions constraint lead to an efficient outcome? In fact, the trade of permits at the company level across such independent regional systems – the so-called ‘linking’ – has lately been described as a promising option (Jaffe and Stavins, 2008; Flachsland et al., 2009). However, before a common permit market is established, the implications of regulatory differences across systems should be carefully assessed.

For a formal analysis, consider a country with an absolute cap $\overline{E}$, and let $C(A)$ denote the convex aggregate cost function for abating an amount A. In autarky, the country faces costs of $C(E_0-\overline{E})$, where E_0 denotes the expected business-as-usual emissions.[11] The government may implement its international obligation by means of a domestic ETS, distributing $Q=\overline{E}$ permits across all emitting agents in its economy. Under perfect market conditions, the resulting equilibrium permit price within the ETS will coincide with the economy’s aggregate marginal abatement costs, i.e. $C'(E_0-\overline{E})$.

[8] A case in point is Russia’s allowance for the Kyoto Protocol’s first commitment period.

[9] In fact, this result is nicely illustrated by the hypothetical cases of India and Russia shown in Table 1.

[10] Note that the condition becomes likelier to hold, the more stringent the envisaged reduction of intensity is; however, the absolute level of probability of hot air then becomes a priori extremely low for both types of targets.

[11] For the purpose of this section perfect foresight is assumed, although in reality both E_0 and the function C are not perfectly known.

In the presence of inter-governmental emissions trading, such as under the Kyoto Protocol, with an expected permit price of p, a cost-minimizing and price-taking government solves

$$\min_{Q} C(E_0-Q)+p(Q-\overline{E}), \tag{7}$$

implying the standard efficiency condition $C'=p$ and thus $Q^*=E_0-C'^{inv}(p)$. In other words, domestic abatement is carried out up to the level $A=C'^{inv}(p)$, at which marginal abatement costs reach the permit price level, whereas the remaining reduction gap (or surplus) $Q^*-\overline{E}$ is met by acquiring (or selling) permits from other countries.

If international permit trading is devolved directly to companies, such as would be the case if different ETS were linked, the government simply sets the cap of its domestic ETS at the internationally agreed level, i.e. $Q=\overline{E}$. Firms receive Q in the form of permits, and by minimizing the costs of meeting their reduction gap, will again satisfy the efficiency condition $C'=p$. In fact, whether governments or firms buy permits on the international market makes in principle no difference (assuming competitive behavior). If firms import Π permits, their emissions rise accordingly. Compliance at the country level is ensured as long as actual emissions correspond to the sum of the initial national allocation and the additional permits, i.e. if $E=\overline{E}+\Pi$.

Consider now the case in which the same country has instead adopted an equivalent intensity target $\overline{\gamma}$, defined by

$$\overline{\gamma}=\frac{\overline{E}}{Y(\overline{E})}=\frac{\overline{E}}{Y_0-C(E_0-\overline{E})}. \tag{8}$$

Without international emissions trade, the regulator allocates $Q=\overline{E}$ permits to the domestic ETS, just as under the absolute target. With Kyoto-style intergovernmental permit trade, the cost minimizing domestic allowance Q^* is determined according to[12]

$$\min_{Q} C[E_0-Q]+p(Q-\overline{\gamma}Y) \Rightarrow -C'[E_0-Q^*]+p(1-\overline{\gamma}dY/dQ)=0 \tag{9}$$

where the term dY/dQ represents the reduction of economic output (with respect to BAU) implied by the emission constraint Q: $Y(Q)=Y_0-C(E_0-Q)$ and thus $dY/dQ=C'$. Substituting back one obtains

$$C'(E_0-Q^*)=\frac{p}{(1+p\overline{\gamma})} \Rightarrow Q^*=E_0-C'inv\left[\frac{p}{(1+p\overline{\gamma})}\right] \tag{10}$$

Domestic abatement is thus carried out up to the level $C'^{inv}\left[p/(1+p\overline{\gamma})\right]$, which is *less* than what was found for an absolute cap. Likewise, the price leading to a zero-trade equilibrium is given by $p=C'$ for the absolute target, but $p=C'/(1-\overline{\gamma}C')$ – i.e. somewhat higher – for the intensity target.

The interpretation of this result is as follows: acquiring an international permit of one ton of CO_2 allows expanding emissions by just one ton in a country constrained by an absolute target, with an according increase in output. Under an intensity target the acquired permit also allows an initial increase of emissions by one unit, but the resulting increase in output has the 'secondary' effect of also increasing the allowed level of emissions $\overline{\gamma}Y$. In other words, the admissible total expansion of output is larger than it would be under an absolute target, and, as a consequence, the regulator of an intensity constrained country is willing to pay more for an emission permit than his counterpart implementing an absolute target.[13]

This characteristic property of the intensity target bears two implications regarding the efficiency and effectiveness of emissions trading between countries with absolute and with intensity targets. To develop an intuition, consider the simple comparison from before, but let there now be two copies of the same country, one with absolute and one with the equivalent intensity target. By definition, both countries have the same emissions level in autarky. Since they are identical, there are no gains-from-trade to be realized, and hence the situation is Pareto optimal. However, if the two countries open up to government-level emissions trading, trade would occur since – as was just shown – their domestic permit price actually differs. More specifically, the intensity constrained country, having the higher price, will buy permits from the other country until the permit price p reaches an equilibrium within the interval $C'<p<C'/(1-\overline{\gamma}C')$. As a consequence, efficiency must break down, since an efficient allocation for two identical countries with convex abatement costs cannot but have the same level of emissions in both countries.

Naturally, permit trade remains mutually beneficial in purely economic terms (otherwise it would not occur), i.e. it raises income in both countries. But it carries a cost in terms of environmental effectiveness: suppose the country with absolute emission cap has sold an amount of Π permits, which are used by the intensity constrained country to expand its output by an amount ΔY. However, compared to the pre-trade state, i.e. $\overline{E}$, the latter's emissions constraint is increased by more than Π, namely by $\Pi+\overline{\gamma}\,\Delta Y$. In other words, the combined total emissions of the two countries experience a net increase of $\overline{\gamma}\Delta Y$ due to the distorted emissions trading.

As demonstrated in Appendix A1 and A2, these arguments hold even in the completely general case of heterogeneous countries with differently stringent reduction targets: free permit trade between countries with absolute and intensity target always leads to an inefficient international allocation of emissions, and net imports (exports) of permits by intensity constrained countries always lead to an increase (decrease) in total combined emissions.

Would the same effect occur if permit trade was devolved to the company level, as suggested by the idea of directly linking different ETS? In this case a country with a national intensity target would initially issue $Q=\overline{E}$ permits to firms by means of, e.g. grandfathering. Firms then face the same incentive-structure as in the absolute cap case, i.e. domestic abatement A will be carried out until $C'(A)=p$, while for the remaining gap, E_0-Q-A, permits Π will be acquired on the joint ETS market. At the end of the commitment period, the country's compliance with its international obligation will be verified by comparing its intensity-based regular allowance plus acquired permits, i.e.

$$\overline{\gamma}Y+\Pi=\overline{\gamma}(Y_0-C[E_0-\overline{E}-\Pi])+\Pi=\overline{E}+\Pi(1+\overline{\gamma}\tilde{C}') \tag{11}$$

where $\tilde{C}'$ is the average marginal abatement cost within the interval $[E_0-\overline{E}-\Pi,\ E_0-\overline{E}]$, with the actual emissions level, $\overline{E}+\Pi$.[14] Because the former is evidently larger than the later, the regulator has an incentive to allocate $\overline{\gamma}\Pi\tilde{C}'$ additional permits within the domestic ETS before the commitment period ends.[15] Thus, the mechanism at work remains the same: by importing permits,

[12] Where brackets are used to emphasize arguments of functions.

[13] These results do not depend on whether the emission policy is implemented by a quantity (cap) or price instrument (tax). The optimal domestic emission tax under an intensity target would be distorted just in the same way as the domestic emission price under a cap. For the intensity target's distortionary effect it also makes no difference whether permit trade takes place during or only directly after the commitment period (ex-post trading), as long as it is anticipated by the regulator.

[14] Arguably, one could subtract the term '$-p\,\Pi$' from ex-post output Y, though this would turn Y into a measure of national income rather than GDP, as it is mostly intended. In any case (because $p<\tilde{C}'$) the implications of the above equation still hold.

[15] The option of issuing additional permits must necessarily be part of an intensity target based ETS, since the main justification for an intensity target is the possibility to allow for more emissions in cases of unforeseen high growth. It would not be necessary for a tax based regulation, but then emissions trade would – if any – be implemented at the government level.

the economy expands, and hence increases its regular emission allowance (and vice-versa).

In sum, although both types of targets are equally well equipped to control emissions in autarky, the 'mechanical' differences between the two instruments cause efficiency to break down in the presence of free permit trade between the two systems. Moreover, if the intensity based regime is a net buyer of permits, global emissions are inflated as a consequence of the trading. A possible solution that restores Pareto efficiency, as demonstrated in Appendix A3, is to subject governments or firms of countries with intensity target to a specific tax τ on traded permits, namely

$$\tau = p\overline{\gamma}/(1-p\overline{\gamma}). \quad (12)$$

However, this approach would need the approval of the countries in question; otherwise the group of countries with absolute target would have to implement this solution self-handedly by levying a tax-equivalent tariff.

7. Incentive to decouple carbon and economic output

For developing countries, compatibility with high economic growth is a condition *sine-qua-non* for engaging in any form of international mitigation effort. Against this backdrop, some authors argue that the intensity target is better suited to accommodate "the need for economic growth" (Herzog et al., 2006), and praise its focus on "decoupling economic growth and emissions growth" (Kim and Baumert, 2002). Accordingly, it would provide a stronger incentive for the "development of clean energy technologies" (Herzog et al., 2006) and the "uptake of low-carbon energy and fuels" (Herzog et al., 2006), thereby helping to bring developing countries on a path of "clean growth" (Herzog et al., 2006).

This section discusses whether and how the choice of abatement investment strategies may depend on the type of the adopted emission target. In an exemplary illustration, the relative preference for abatement by intensity-reducing 'decarbonization' versus 'end-of-pipe' (e.g. CCS) is investigated by means of a formal model. Intuitively, an intensity target seems to set a stronger incentive for decoupling growth and emissions because it allows the regulator to focus on the technological transformation of the energy system without having to worry too much about breaching a given absolute emissions ceiling. However, this does not imply that under an absolute cap the incentive to do so is necessarily lower. In fact, it is well established that in a deterministic setting intensity and absolute targets are perfectly equivalent (Ellerman and Sue Wing, 2003), meaning that in such circumstances all incentives and technology choices would be identical.[16]

Therefore, a necessary condition for breaking the symmetry between the two types of targets is the presence of uncertainty. With an intensity target, abatement uncertainty may under some conditions be reduced (see Section 4), but would this also lead to a different – namely 'greener' – abatement strategy? Such a question has been addressed by Krysiak (2008), who formally analyzed the influence of uncertainty on the technology choice at the firm level. He considered a linear marginal abatement cost curve, and assumed two different investment options for lowering abatement costs: reducing the curve's slope and reducing its overall level (i.e. the intercept). For his model, he proposed to interpret the first option as end-of-pipe measures like CCS, which provides a flexible abatement with approximately constant – albeit potentially high – marginal costs, and the latter as investments into renewable or nuclear energy options, characterized by higher upfront costs and inelastic – albeit potentially cheaper – abatement supply.

If one generalizes Krysiak's results and interprets the curve as the economy's aggregate abatement cost function, it can be used to evaluate how uncertainty affects the choice between the two options. Namely, with an analogous and straightforward calculation it can be shown that in the cost-minimizing strategy, investments of the second type (renewables, nuclear) only depend on the mean expected abatement, while investments of the first type (like CCS) are in addition positively correlated to the uncertainty on the expected abatement. In other words, CCS-like investments will be higher for the target with higher uncertainty. This is an intuitive result: a flexible technology with relatively flat marginal costs becomes more valuable the higher the uncertainty about the required abatement. Therefore, within the framework proposed by this model, the intensity target would be a better promoter of a thorough decarbonization of the energy system than the absolute cap only if it actually reduces uncertainty vis-à-vis the latter, i.e. if Eq. (4) holds.

However, a significant shortcoming of the previous analysis is that it abstracts from the specific properties of the two targets by merely considering the different levels of abatement uncertainty they imply. For a more specific analysis, their particular coupling to emissions and GDP should be taken explicitly into account. To illustrate this point, let us consider the following formal analysis of the relative employment of the abatement strategies 'reduction of emission intensity' and 'end-of-pipe measures' under intensity and absolute target, where only the first is taken to represent real 'decarbonization'.

Specifically, let the total costs for lowering the economy's BAU emission intensity γ by a percentage s be given by the convex function $C[s]$, while constant marginal costs x are assumed for the end-of-pipe abatement. The former is a common assumption (e.g. Nordhaus, 1993) justified, e.g., by the need to use ever less suitable sites for renewable energy production (wind, solar) and the associated increasing integration and storage costs. The latter is a simplifying assumption, which would be fully valid only if x is interpreted as the price of an emission permit on the international market.[17] To a lesser extent, it can also be viewed as a representation of CCS, which – in comparison to renewable or nuclear energy – is characterized by relatively high operational costs, provoking a switch-off if the price of carbon falls below a certain threshold or would be suspended completely.[18]

In formal terms, total abatement costs for a given emissions target T can then be expressed as ($E[s]$ denoting emissions as function of the intensity parameter s)

$$TC[T] = x(E[s]-T)+C[s] = x(Y\gamma(1-s)-T)+C[s] = x(E(1-s)-T)+C[s] \quad (13)$$

where the target T is equal to $\overline{E}$ for an absolute and $\overline{\gamma}\,Y$ for an (equivalent) intensity target. For a regulator with risk aversion, here incorporated through a parameter $\lambda > 0$, the optimal choice for s may be determined by

$$\min_{S} < TC > +\lambda\sigma_{TC}. \quad (14)$$

The average costs are the same for both targets, but the uncertainty of costs (σ_{TC}) depends on the abatement uncertainty, which is generally not the same. Namely, computing the standard

[16] This equivalence also implies that absolute and intensity targets are equally suitable to define targets with room for some emission growth, as expected – at least in the near term – to be necessary for developing countries.

[17] Within this interpretation, the present analysis would asses in how far the intensity sets a stronger incentive for domestic abatement (versus buying one's way out) than an absolute target.

[18] According to study by McKinsey (2008), total costs for CCS in 2030 could be between 30€ and 45€ per ton, of which around 50% are variable costs that could be saved by switching-off the CCS process.

deviation of Eq. (13) shows that $\sigma_{TC}=x\sigma_A$, where σ_A is the target-specific abatement uncertainty, which depends on the degree of intensity reduction s. As shown in Appendix A4, reducing the emission intensity γ produces a stronger reduction of cost uncertainty under an absolute than under an intensity target, which leads to the result that the optimal reduction of intensity is in fact higher under an absolute target.

The underlying intuition is the following: reducing the emission intensity by a percentage s leads to a decrease in the variability of emissions by a factor $(1-s)$, which has an unambiguously positive (i.e. decreasing) effect on the abatement and (thus) cost-uncertainty under a cap. However, under an intensity target the abatement uncertainty comprises (see Eq. (3)) two additional terms, which dampen the effect of a reduced emission variability. This is due to the specific mechanics of the intensity target, which performs best if the variability of emissions is not too low, as can be seen by considering the limit case with constant known emissions ($\sigma_E=0$): an absolute cap then implies zero abatement uncertainty ($\sigma_{A\_Cap}=0$), whereas uncertainty would remain finite ($\sigma_{A\_Int}=\overline{\gamma}\ \sigma_Y$) for the intensity target, due to its coupling to uncertain economic output.

In sum, it was shown that in the presence of uncertainty, the incentive to implement one or the other abatement measure may indeed differ for the two types of emission targets. However, the intuitive idea that intensity targets generally provide a stronger incentive for the decoupling of growth and emissions was rebutted exemplarily in an analysis of intensity-oriented versus end-of-pipe abatement, where the incentive to pursue the first was shown to be stronger for the absolute target. However, due to its stylized character the analysis should be understood as a starting point for further investigations on whether intensity and absolute targets could – in models with different sectors and abatement technologies – lead to different domestic outcomes in terms of technology choices. All the more so since in the literature most arguments with regard to the intensity target's incentive towards 'decoupling' are based on an intuitive and therefore rather vague reasoning, without giving formal definitions (e.g. meaning of 'clean growth') that would have allowed a more rigorous assessment of their merit.

8. A substitute for banking and borrowing?

An intuitive appeal of the intensity target is its 'smoothing over time' effect: a country can retain a higher share of emissions in higher-than-expected growth periods, since (supposedly) these will be offset by lower emission allowances in subsequent lower-than-expected growth periods. Based on this idea, Sue Wing et al. (2009) compare intensity and absolute targets with respect to their "temporal stability" – i.e. volatility of abatement over time – and find a higher stability for the intensity target if, again, the condition of Eq. (4) is met. A natural extension of their analysis is the question of whether the intensity target could reduce volatility to the extent of becoming a viable substitute for a banking and borrowing ('banking' for short) scheme. The latter is known to enhance dynamic efficiency (Bosetti et al., 2009), but policy makers tend to be cautious especially with unfettered borrowing, fearing a destabilization of the whole system when uncontrollable amounts of debt accumulate (Boemare and Quirion, 2002). Hence, the question of this section is whether the same level of abatement volatility of an absolute target with banking and borrowing can be reached by just employing a plain intensity target.

To derive how banking reduces fluctuations under an absolute target, consider a two-period model, where emissions of period one and two are assumed to behave according to

$$E_1 = E_0+\varepsilon_1$$
$$E_2\big|_{E_1} = E_0+\beta(E_1-E_0)+\varepsilon_2\sqrt{1-\beta^2} \tag{15}$$

Here, $.\big|_E$ denotes the conditional value operator, and the ε_i are independent and identically distributed random variables with zero mean and standard deviation σ_E, while β is a parameter with $|\beta|\le 1$. This set-up conveniently implies $\sigma_{E1}=\sigma_{E2}=\sigma_E$ for the individual standard deviations, and a temporal correlation of β between E_1 and E_2. The latter can be used to capture the influence of business-cycle dynamics on emissions, e.g. with a negative value for β higher-than-expected emissions in a first commitment period will likely be followed by lower-than-expected emissions in the next period.[19]

Under an absolute cap $\overline{E}<E_0$, the optimal amount of banking B – once first period emissions E_1 have realized – can be derived by requiring the expected period two abatement effort A_2 to be equal to the one of the first period[20]

$$\langle A_2\rangle\big|_{E_1} = \langle E_2\rangle\big|_{E_1} - \overline{E}+B \overset{!}{=} A_1 = E_1-\overline{E}-B. \tag{16}$$

This yields the following expression for the optimal amount of banking in period one:

$$B=\frac{1}{2}(E_1-\langle E_2\rangle\big|_{E_1}) = \frac{1}{2}(E_1-E_0)(1-\beta). \tag{17}$$

The result follows intuition: with perfect temporal correlation ($\beta=1$), emissions are a priori constant over time, leaving no scope for banking. In the opposite case ($\beta=-1$), the entire period-one deviation from the expected value E_0 is banked, as it is always followed by an equal – but opposite direction – deviation in the next period. Without any temporal correlation ($\beta=0$), half of the difference with respect to the expected value is banked.

When this strategy is pursued, the resulting abatement volatility for the first and second period can be computed (shown in Appendix A.5) to

$$\sigma_{A1} = \sigma_E\left(\frac{1+\beta}{2}\right)$$
$$\sigma_{A2} = \frac{\sigma_E}{2}\sqrt{3(1+\beta)(5/3-\beta)} \tag{18}$$

As expected, no 'smoothing' effect would occur for a temporal correlation of one, whereas in the opposite case ($\beta=-1$) volatility of abatement could be eliminated completely, i.e. $\sigma_{A1}=\sigma_{A2}=0$. With negligible temporal correlation ($\beta=0$), it is still reduced by 50% vis-à-vis the no-banking case in the first period, but only at the cost of an increase of 12% in the second period. The latter, however, is mostly due to the short time horizon, which necessitates the settling of the 'account' in period two; this effect would thus be (much) smaller for longer-term targets with several commitment periods.

Therefore, banking always decreases the abatement volatility of the first period, whereas in the second period this is only the case if there is a cyclical behavior with sufficiently negative temporal correlation ($\beta<-1/3$). The net effect, i.e. the sum of the change over both periods, is always to reduce volatility. For instance, with a weakly cyclical behavior of $\beta=-0.1$ one obtains a change in variability of -55% and +9% for the first and second period, respectively, corresponding to an average net effect of -23%.

[19] Implicitly, such an argument is based on the assumption that countries adopt reduction obligations that – unlike in the Kyoto Protocol – span over more than one commitment period. There is indeed a strong case to do so, e.g. to stabilize long-term expectations of private investors (Blyth et al., 2007).

[20] As implied by the efficiency condition of constant marginal costs, if the abatement cost function is time invariant.

This can now be compared to the level of volatility that is achieved with a plain intensity target. Without banking, cyclical behavior must not be taken into account, and the average reduction with respect to an absolute target thus follows Eq. (3). Accordingly, in order for the intensity target to reduce volatility by 50%, a very high correlation between emission and GDP shocks of at least $\rho = 0.87$ would be needed, and – in the most favorable case with regard to the parameter values of $\overline{\gamma}\sigma_Y/\sigma_E$ – at least $\rho = 0.6$ for an average reduction of 20%.

With the latter, the reduction would be comparable in size to the effect of banking under an absolute target, and since the value $\rho = 0.6$ is not completely implausible, the intensity target can indeed be seen as a possibility to substitute banking and borrowing to some extent—conditional on suitable parameter values and in reference to a very short two-period framework. Said differently, an intensity target with proven and significant ability to reduce uncertainty lowers the need to employ banking for an intertemporal smoothing of the abatement effort. Naturally, the converse also holds: when banking provisions are already put in place, the added value of an intensity target becomes much lower.

But as long as the intensity target's effect is itself somewhat undetermined, i.e. whether and by how much it decreases uncertainty is only imperfectly known due to uncertain parameter values, an absolute cap with banking provisions – even limited ones – appears preferable, since it always leads to a net reduction of abatement volatility. Moreover, the intensity target can never substitute explicit banking when it comes to setting an incentive for early abatement, a policy objective in its own right (Bosetti et al., 2009).

9. Conclusion

Intensity targets are often portrayed as an attractive alternative to Kyoto-style absolute emission caps, especially for developing countries. Amongst others, China recently announced that it intends to implement such a target.[21] In this paper, five policy relevant properties that could – and have been – associated with the intensity target are discussed and formally assessed by means of simple analytical models.

First, the conditions under which an intensity target lowers cost-uncertainty – with reduction uncertainty taken as proxy – were revisited. In autarky, this is only the case when parameter values fulfill conditions that do not self-evidently hold nor are easily verifiable by empirical analysis. Moreover, even in favorable cases would the potential gain – in terms of uncertainty reduction – likely remain modest. Last but not least, any potential decrease in uncertainty becomes less significant when considering that cost-uncertainty can be reduced to some extent also for absolute targets by participation in international emissions trading.

Second, whether or not an intensity target lowers the incidence of hot air is shown to depend on the same formal condition as the reduction of cost-uncertainty. Therefore, the same doubts about the outcome – due to uncertain parameter estimates – persist.

Third, an analysis of emissions trading between countries with absolute and intensity target was carried out. The relevance of this question is underpinned by the currently observable tendency towards fragmentation in international climate policy (Victor, 2007). Within a two-country model, the intensity target is shown to create an upward distortion in the permit price, i.e. the price becomes higher than actual marginal abatement costs. Two implications arise: first, due to the 'mechanical' differences between the two targets, efficiency breaks down if permits are traded freely between the two systems, leading to allocations not satisfying Pareto efficiency. Second, emissions trading between the two systems increases (decreases) global emissions whenever the country with intensity target is a net buyer (seller) of permits.

Fourth, it was argued and shown exemplarily that the incentive for a lasting transformation of the energy system by means of low-emission technology (decarbonization) is not necessarily stronger under intensity than under an absolute target. In the chosen analytical model this is due to the fact that a reduction of emission intensity also implies a reduction of emission uncertainty, which always has a positive impact under an absolute cap, but an ambiguous one under the intensity target. In fact, the latter – in order to work well – does not require the lowest possible emissions uncertainty, but one that is well-balanced with the uncertainty of output.

Fifth, the intensity target's potential to act as a substitute for banking and borrowing was assessed. The possibility of doing so is suggested by the way it adjusts the emission allowance to unexpected high or low growth, similar to a buffer-mechanism against business-cycle induced fluctuations. It was shown that banking and borrowing under an absolute cap unambiguously reduces abatement volatility, especially when emission targets extend over multiple commitment periods. Intensity targets without banking can also decrease volatility, but the magnitude will even in favorable cases (in terms of parameters) not exceed the lower end of what can be achieved by borrowing and banking.

In sum, three out of five potential benefits of the intensity target are linked to uncertainty and were found to be contingent upon the values of parameters, in particular the correlation ρ between shocks in future emissions and future economic output. There is little doubt that the stability and predictability of abatement commitments have a significant influence on the acceptability and stringency of emission targets proposed to developing countries (IEA, 2003)—e.g. in a world without uncertainty a BAU target on emissions would represent a no-regret option. However, as the analysis in this paper has shown, even though the intensity target can reduce uncertainty under some conditions and for some countries, the contingency of its performance on the new and difficult to estimate parameter ρ (among others) introduces new uncertainty, which in a real-world application might turn the potential benefit into a liability.

This is further aggravated when taking into account alternative measures that can be implemented under absolute caps – like international emission trading and banking/borrowing provisions – which are guaranteed to reduce uncertainty and at the same time come without the potential pitfalls of the intensity target. To increase developing countries' incentive to join international mitigation efforts, they could be endowed with – at least initially – generous emission allocations, so as to ensure they become permit sellers. Theoretically, such measures are feasible also under an intensity target—but in this case their implementation would be less straightforward and could require additional provisions to ensure efficiency, as the analysis of international emissions trading has shown.[22]

Finally, a robust advantage of the intensity target in terms of the generated incentives for decarbonization could not be verified. Although intuitively appealing, the actual incentive for adopting one or the other abatement strategy may depend on techno-economic details, not warranting a general conclusion that lowering the emissions intensity by means such as renewable energy and

[21] See also the article "U.S. and China to Go to Talks with Emissions Targets" in the New York Times, appeared online on 26 September 2009.

[22] Other 'technicalities' potentially complicating the implementation of an intensity target include the question of MER versus PPP measurement of output, and the fact that with an intensity target the actual emission allowance is only known with a considerable time delay, when official GDP statistics are released (see Herzog et al., 2006).

fuel-switching is always more appealing under an intensity than under an absolute target. Admittedly, the analysis presented here represents only the first step, while for a definite answer more research on the specific cost-structures and macroeconomic links of the various abatement technologies is needed.[23] However, for the time being absolute caps represent the more robust target choice, not least because of their simplicity and high transparency.

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Appendix

A.1. Proof that emissions trading between a country with absolute and one with intensity target always leads to an inefficient allocation of emissions, in the sense that the same combined emissions level could be reached at lower costs.

For an arbitrary pair of countries, with subscript '*A*' for absolute target and '*I*' for intensity constrained, an efficient after-trade emission allocation requires the equalization of marginal abatement costs, i.e.

$$C'_A[E_{A0}-\overline{E}+\Pi] = C'_I[E_{I0}-\overline{\gamma}Y-\Pi] \tag{A.1}$$

Following the cost-minimization rationale of Eqs. (7) and (9), the implicit permit demand functions of each regulator (assuming 'Kyoto-style' trade at government level), for a given permit price *p*, are, respectively

$$-C'_A[E_{A0}-Q_A^*]+p=0 \tag{A.2}$$

$$-C'_I[E_{I0}-Q_I^*]+p(1-\overline{\gamma}dY_I/dQ_I)=0 \tag{A.3}$$

Note that the arguments (in brackets) correspond to the amount of net domestic abatement, just as in Eq. (A.1). Imposing market clearance by equating the price *p* yields

$$C'_A\left[E_{A0}-Q_A^*\right] = \frac{C'_I[E_{I0}-Q_I^*]}{(1-\overline{\gamma}dY_I/dQ_I)}, \tag{A.4}$$

which evidently contradicts the efficiency condition given in Eq. (A.1) since $C'_A > C'_I$.

In other words, the last equation shows that in equilibrium marginal abatement costs in the country with absolute target are too high with respect to the efficient level.

A.2. Proof that emissions trading between an arbitrary pair of countries with different types of targets leads to an increase in combined emissions if the country with absolute target is a net seller, and to a decrease if it is a net buyer of permits.

Suppose in the trade equilibrium the country with absolute cap sells an amount (positive or negative) of Π permits to the country with intensity target. In the pre-trade state, the latter's emissions constraint was implemented by means of an ETS with a total allowance volume *Q*, satisfying

$$Q=\overline{\gamma}Y(Q). \tag{A.5}$$

After trading the Π permits, the regulator adjusts the number of allowances in his domestic ETS, to be in line with the new constraint

$$Q+\Delta Q=\overline{\gamma}Y(Q+\Delta Q)+\Pi. \tag{A.6}$$

For the combined emissions to stay constant, the change ΔQ must coincide with Π. However, assuming positive abatement costs and focusing on the case of permit import ($\Pi>0$), one immediately obtains

$$\overline{\gamma}Y(Q+\Delta Q)+\Pi > \overline{\gamma}Y(Q)+\Pi = Q+\Pi \Rightarrow \Delta Q > \Pi \tag{A.7}$$

and the case $\Pi<0 \Rightarrow \Delta Q < \Pi$ accordingly.

A.3. Application of a tax as corrective policy measure

Since the distorted permit price lies at the heart of the trade incompatibility between regions with absolute and intensity based targets, it seems natural to impose a tax on permit trade with the intensity constrained country. To reflect the true marginal productivity of emissions, an *ad valorem* tax τ of $\tau = p\overline{\gamma}/(1-p\overline{\gamma})$ on traded permits must be accepted by the country with the intensity target or, alternatively, imposed on it from the outside in form of a tariff (within government-level AAU trade à la Kyoto). To see this, consider again how the government in the intensity-constrained country determines its demand for international permits by minimizing total compliance costs as expressed in Eq. (9), now modified by the tax τ

$$\min_Q C[E_0-Q]+p(1+\tau)(Q-\overline{\gamma}Y) \Rightarrow p(1+\tau)(1-\overline{\gamma}dY/dQ) = C'[E_0-Q]. \tag{A.8}$$

Using $Y(Q)=Y_0-C[E_0-Q]$ and the above definition for τ, one immediately obtains $p=C'$, i.e. the desired efficiency condition of price = marginal abatement costs.

In effect, the tax modifies the permit price *p* by letting it appear as somewhat higher.

A.4. Optimal reduction s of emission intensity under absolute and intensity target

The first order optimality condition is a function of the cost uncertainty's derivative with respect to *s*, which in Appendix A.4 is shown to be always less negative for the intensity than for the absolute target. In other words, computing the standard deviation of Eq. (13) is straightforward for the absolute cap and yields

$$\sigma_{TC\_Cap} = x(1-s)\sigma_E, \tag{A.9}$$

where σ_E is the standard deviation of BAU emissions. With average costs of $\langle TC \rangle = x(E_0(1-s)-\overline{E})+C[s]$ for both targets, substituting back in Eq. (14) and taking the first derivative yields a simple first-order condition for the optimal percentage reduction *s* under the absolute target

$$C'[s] = x(E_0+\lambda\sigma_E). \tag{A.10}$$

Since the cost function *C* is convex, this determines a unique value for *s*. In case of the intensity target, average costs do not change, but their standard deviation becomes

$$\sigma_{TC\_Int} = x\sqrt{(1-s)^2\sigma_E^2+\overline{\gamma}^2\sigma_Y^2-2\overline{\gamma}(1-s)\rho\sigma_E\sigma_Y} = x\sigma_{A\_Int}. \tag{A.11}$$

For the corresponding first-order condition of the objective function one obtains

$$C'[s] = x\left(E_0+\lambda\sigma_E\frac{((1-s)\sigma_E-\overline{\gamma}\rho\sigma_Y)}{\sigma_{A\_Int}}\right). \tag{A.12}$$

[23] For a different aspect, however, the incentive structure of the intensity target could be questioned: namely, it could be used to justify an unduly low abatement effort, when political leaders cling to an upwardly biased GDP expectation (or ambition), which – for them – implies a generous emissions allowance and, consequently, less need for abatement.

For any s within the unit interval, and any $|\rho|<1$, the right hand side of this equation is always smaller than the corresponding value for the absolute target, Eq. (A.10). To see this, consider the fraction part from the last equation, written as a square root

$$\sqrt{\frac{((1-s)\sigma_E-\overline{\gamma}\rho\sigma_Y)^2}{\sigma_{A\_Int}^2}}=\sqrt{\frac{(1-s)^2\sigma_E^2+\rho^2\overline{\gamma}^2\sigma_Y^2-2\overline{\gamma}(1-s)\rho\sigma_Y\sigma_E}{(1-s)^2\sigma_E^2+\overline{\gamma}^2\sigma_Y^2-2\overline{\gamma}(1-s)\rho\sigma_E\sigma_Y}}<1, \tag{A.13}$$

where the expression for abatement uncertainty σ_{A_Int} from Eq. (A.11) was used. The numerator in Eq. (A.12) can become negative, but in this case the claim still holds.

If the right-hand-side of Eq. (A.12) is always smaller than the one of Eq. (A.10), it follows by the convexity of C that the optimal s under an intensity target must always be lower than under an absolute cap. The potentially negative numerator in Eq. (A.12) corresponds to the case in which an increase of s has a counterproductive effect, i.e. it leads to an increase in cost uncertainty. Note that this will always be the case for sufficiently high s.

A.5. Computation of the volatility of abatement for period one and two with an absolute cap $\overline{E}$ and optimal banking B.

Given the definition of emissions in period one and two from Eq. (15), and the expression for the optimal banking in Eq. (17), it follows for the average abatement in the first period

$$\langle A_1\rangle=\langle E_1\rangle-Q-\langle B\rangle=E_0-Q\equiv A_0 \tag{A.14}$$

while the average for the squared abatement is

$$\begin{aligned}\langle A_1^2\rangle&=\langle (E_1-Q-B)^2\rangle=\langle (A_0+\varepsilon_1-B)^2\rangle\\&=\langle A_0^2\rangle+\langle \varepsilon_1^2\rangle+\frac{(1-\beta)^2}{4}\langle \varepsilon_1^2\rangle+2A_0\langle \varepsilon_1\rangle\\&\quad-2A_0\langle B\rangle-\langle \varepsilon_1(\varepsilon_1)(1-\beta)\rangle\\&=A_0^2+\left(1+\frac{(1-\beta)^2}{4}-(1-\beta)\right)\sigma_E^2=A_0^2+(1+\beta)^2\frac{\sigma_E^2}{4}\end{aligned} \tag{A.15}$$

This gives the desired result for the first period standard deviation in the actual abatement

$$\sigma_{A1}=\sigma_E\left(\frac{1+\beta}{2}\right). \tag{A.16}$$

The average abatement in the second period is again A_0

$$\langle A_2\rangle=\langle E_2\rangle-Q+\langle B\rangle=E_0-Q=A_0. \tag{A.17}$$

For the average of the squared abatement in period two one computes

$$\begin{aligned}\langle A_2^2\rangle&=\langle (E_2-Q+B)^2\rangle=\langle E_2^2\rangle+Q^2+\langle B^2\rangle-2QE_0+2\langle BE_2\rangle\\&=\sigma_E^2+A_0^2+\frac{1}{4}(1-\beta)^2\sigma_E^2+(1-\beta)\langle \varepsilon_1(E_0+\beta\varepsilon_1+\varepsilon_2\sqrt{1-\beta^2})\rangle\\&=\sigma_E^2+A_0^2+\frac{1}{4}(1-\beta)^2\sigma_E^2+\beta(1-\beta)\sigma_E^2=A_0^2+\frac{\sigma_E^2}{4}(5+2\beta-3\beta^2)\end{aligned} \tag{A.18}$$

which allows to obtain the desired expression for the standard deviation

$$\sigma_{A2}=\frac{\sigma_E}{2}\sqrt{5+2\beta-3\beta^2}=\frac{\sigma_E}{2}\sqrt{3(1+\beta)(5/3-\beta)}. \tag{A.19}$$

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