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Can China benefit from adopting a binding emissions target?

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Abstract:

In the run-up to the Copenhagen climate summit, the USA announced an emissions reduction target of 17% by 2020 (relative to 2005), and the EU of 20% to 30% (relative to 1990). China offered a reduction target for the CO_2-intensity of its economy, but rejects a legally binding commitment. We use the targets announced by the EU and the USA to analyze the potential gain for China if it were to adopt a binding emissions target and join an international emissions trading scheme. We show that China would likely benefit from choosing a binding target well below its projected baseline emissions for 2020.

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1. Introduction

The UN climate summit in Copenhagen in December 2009 did not bring forth a legally binding international agreement to reduce global greenhouse gas emissions. One of the issues that remain unresolved is the question whether emerging economies such as India and China should adopt binding targets for their greenhouse gas (GHG) emissions. Scientists argue that global emissions should peak within the next years, and decline thereafter in order to avoid dangerous climate change. However, officials from India and China argue that binding emissions targets may hamper the growth of their economies, and highlight the responsibility of the industrialized countries to first cut their emissions substantially.

The economics literature offers a number of theoretical arguments why the adoption of a binding emissions target may be in a country's own interest. In particular, a binding commitment to stabilize GHG emissions may be seen as a necessary requirement in order to join an international emissions trading scheme.[1] By joining a trading scheme, a country can generally achieve a higher welfare than in a situation of autarky, where only domestic abatement efforts are undertaken. E.g., if the country faces low abatement costs, trade in permits allows the country to sell some of its low-cost abatement options to countries with a higher willingness-to-pay. Therefore, trade in permits can be in a country's interest even if climate stabilization is not one of its political priorities. Furthermore, a country with low abatement costs may benefit from the adoption of an ambitious reduction target: this limits the total supply of permits, and induces a higher permit price. Under some conditions, this allows the country to achieve higher revenues from selling permits.

The goal of this paper is to analyze whether China, that has so far not offered to accept a legally binding emissions target, may benefit from doing so. To this end, we analyze China's welfare when it joins an international emissions trading scheme and is free to choose its own emissions target. We present a numerical analysis that is based on recent estimates of marginal abatement cost curves, and on the reduction targets announced by the USA and the EU. Taking the EU's and the USA's commitments as given, we endogenize China's optimal emissions target under the simplifying assumption that China behaves non-cooperatively vis-à-vis the other players, while the EU and the USA set their targets cooperatively or independently of China. The EU's commitment to choose a more stringent reduction target when other large emitters adopt more ambitious targets reveals a cooperative strategy.[2]

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[1] In this paper, we focus on bottom-up emissions trading on the firm level, see Flachsland et al. (2009).

[2] If the EU were to behave non-cooperatively, a more stringent reduction target by China would imply that the EU should set a less ambitious target, in order to reduce the losses implied by the rise in the price of permits resp. offsets (see Carbone et al., 2009).

We compare China's welfare when it joins a trading scheme with a situation of autarky, where only domestic abatement efforts are undertaken. The additional welfare under emissions trading is China's surplus from trading. Whenever China can achieve a high surplus, the adoption of a binding emissions target is likely to be in China's own interest. Furthermore, if China's optimal emissions cap (in 2020) is lower than baseline emissions, then trade in permits is also superior to selling offsets (in terms of welfare). If China participates only in a market for offsets, but does not adopt a binding emissions target, the outcome is comparable to a situation with trade in permits where China's cap is given by its baseline emissions.[3] Chen (2005) argues that China should play an active role in offset markets rather than to accept a binding emissions target. Our results deviate from this, because we integrate China's benefits from trading permits explicitly into the analysis, and assume that China is free to choose its own emissions cap.[4]

Before we move on to the numerical analysis, we present a simple model to compute the optimal choice of the abatement target of a country that joins an international emissions trading scheme. We show that even when the participating country does not value climate stabilization, it may nevertheless benefit from committing to reduce its emissions. This holds if the country uses the trading scheme primarily to generate revenues, and the country's marginal abatement cost curve (MAC) is less steep than the slope of the combined MACs of the other countries in the trading scheme. We also consider situations where some other country's choice of a cap depends on China's reduction target. This is motivated by the EU's commitment to adopt a more stringent reduction policy if other large emitters also adopt more ambitious targets. We show that this commitment can induce contributions to a reduction of global emissions by countries that do not value climate stabilization and would otherwise not be willing to contribute to this public good. This is because the EU's choice of a lower cap in response to a more ambitious reduction target can *amplify* the effect on the permit price, which creates additional incentives for these countries to reduce their cap.

In Section 3, we use the theoretical results to analyze constellations where China links its (to be established) emissions trading scheme with the EU-ETS, or with a (to be established) US-ETS, or with both of them. We find that in most of the cases we consider, China benefits from making a significant contribution to climate stabilization. For the analysis of welfare maximization, we need an estimate of China's valuation of reduced emissions. Since this

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[3] If the implementation and monitoring of offset projects entails higher transaction costs than selling permits, the option to participate in an emissions trading scheme becomes even more attractive (compared to selling offsets).
[4] Lutter (2000) highlights uncertainty about future greenhouse gas emissions in developing countries as an impediment towards their participation in international climate treaties. To manage these risks, the author argues that these countries should index their caps to variables that predict emissions in the absence of caps.

valuation can not be observed, we use an indirect approach to estimate it. Namely, we assume that the USA's and the EU's announced reduction targets reflect their own marginal valuation of abatement, in a scenario where each of these regions abates domestically and has access to an outside offset market. We, then, scale the average of these numbers using China's projected GDP for 2020 to obtain an estimate of China's valuation of reduced emissions. This approach yields a consistent estimation of China's valuation under the assumption that the vulnerability of China's economy to the adverse effects of climate change per unit of GDP is (roughly) comparable to the vulnerability of the EU's and the USA's economy.

Carbone et al. (2009) use a Nash-equilibrium approach to determine different regions' choice of a cap in an international emissions trading scheme. The model is embedded in a general-equilibrium framework with trade. Therefore, terms-of-trade effects affect countries' choices of a cap, as well as environmental considerations and their incentives to obtain revenues from selling permits. An important insight offered by this paper is that – in an environment where countries set their reduction targets *non-cooperatively* – a trading scheme that covers many world-regions may perform less well than a set of smaller schemes where countries with a high willingness-to-pay for reductions are matched with low-abatement-cost countries. The reason for this is that within a smaller scheme, the low-abatement-cost country has a stronger effect upon the permit price, which makes it relatively more attractive to choose a lower cap in order to achieve higher revenues from permit sales. In a larger scheme, an individual country's impact on the permit price is less significant, hence, the incentives to issue more permits (or to produce 'hot air') become more dominant. The authors show that a trading scheme that links China with the EU (optionally including also the FSU-region) is a stable constellation that achieves a high total amount of reduced emissions, higher than a larger trading scheme that includes also the USA.[5]

Our findings point in a similar direction, but we do not assume non-cooperativeness in the overall choice of caps. Instead, we focus on the decision of an individual country, and treat the other countries' targets as exogenous. This approach reveals more clearly the trade-offs faced by a low-abatement-cost country such as China, and allows for cooperative reduction targets chosen by other countries. Our results confirm the prediction that a smaller trading scheme that links only China with the EU may sometimes achieve higher overall reductions than a larger scheme that involves also the USA. Whether this is the case, depends (among

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[5] A pioneering work on emissions trading with endogenous reduction targets is Helm (2003). As Carbone et al. (2009), the author assumes that countries set their reduction targets non-cooperatively, and finds that the establishment of an international emissions trading scheme can lead to higher emissions. Hahn (1984) analyzes a market in which firms rather than governments can exercise monopoly power to manipulate the permit price.

other things) on China's valuation of reduced GHG emissions. These findings weaken the presumption made by other authors that a transatlantic carbon market that links the EU with the USA is an important step towards a 'level carbon playing field' that achieves a maximum amount of efficiency in global climate protection (Sterk and Kruger, 2009). A set of smaller schemes (e.g. one that links China with the EU-ETS, and a separate scheme that links the USA with India or Brazil) may under some conditions achieve higher emissions reductions.

2. A simple model

Let "home" be a country or region that plans to join an international emissions trading scheme. Other countries in the trading scheme are summarized as "foreign". Suppose an abatement target for foreign ($\overline{A}_f$) has already been fixed, and consider home's choice of a target $\overline{A}_h$. Home's abatement target is the difference between home's emissions under a business-as-usual scenario (BAU_h), and home's emissions cap (Cap_h) for the trading period of interest: $\overline{A}_h = BAU_h - Cap_h$. Under emissions trading, home's actual emissions (E_h) can be above or below the cap. Home's *actual* abatement (A_h) is given by: $A_h = BAU_h - E_h$.

In the following, we analyze whether home is willing to contribute to global emissions reduction, hence, to choose a positive abatement target $\overline{A}_h > 0$. In a first step, we assume that the damages of climate change are not taken into consideration by home's policy maker. Even in this case, home may adopt an emissions reduction target and join an international trading scheme in order to reap revenues from selling permits. Home's revenues (R_h) from trading are positive if it becomes a seller of permits in the trading scheme, but the cap is not chosen too high so that the permit price remains positive. This is illustrated in Figure 1.

Figure 1: Home's revenues from emissions trading (R_h) as a function of home's cap (Cap_h)
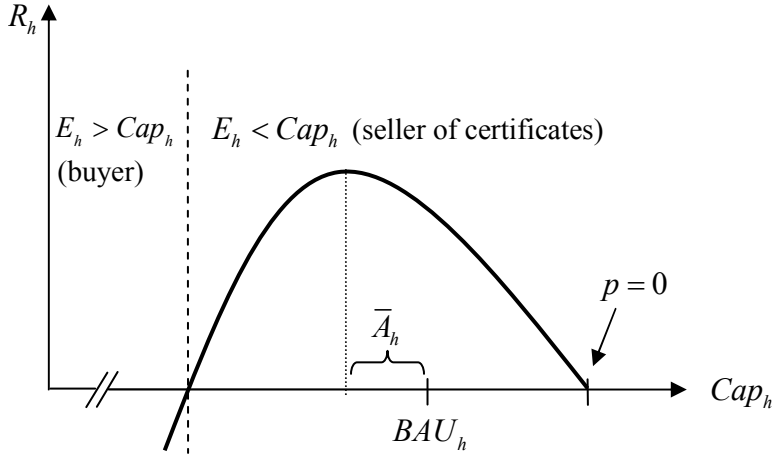
As Figure 1 illustrates, home's revenues from emissions trading reach a maximum in the range where home is a seller of certificates but the price p remains positive. If home seeks to maximize its revenues, and the maximum of the curve R_h lies below BAU_h (as in the Figure), then home adopts a binding emissions reduction target ($\bar{A}_h > 0$). Otherwise, it prefers to produce "hot air" by choosing a cap larger than BAU emissions ($\bar{A}_h < 0$).

If firms can buy or sell certificates and trade them internationally, emissions are reduced until the marginal abatement costs in home and in foreign equal the market price of certificates p :[6]

$$p = MC_h(A_h) = MC_f(A_f) \tag{1}$$

Figure 2 shows home's revenue from emissions trading under the assumption of linearity:

Figure 2: Home's revenue from emissions trading (linear MACs)
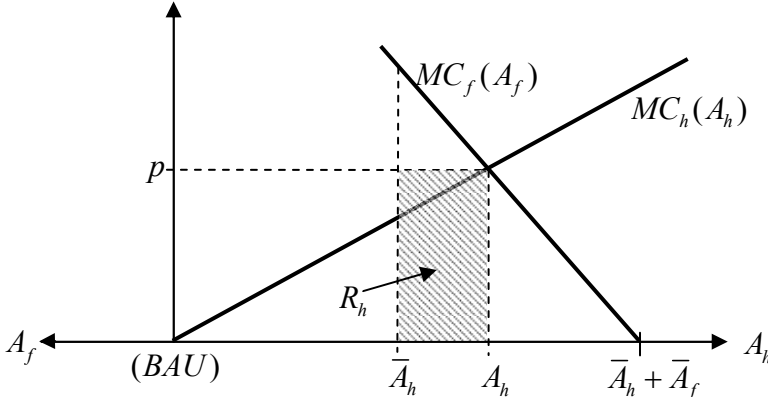
A strategy of revenue-maximization requires that home seeks to maximize R_h, while the abatement costs (incurred by the firms) are neglected. In contrast, a strategy of profit-maximization requires that the total abatement costs are subtracted from the target function, a plausible assumption when there are more efficient ways of taxation (e.g. lump sum taxes). However, given the constraints that governments face when raising taxes, selling permits may be an effective way to finance public spending. Hence, governments may sometimes be more interested in maximizing revenues rather than profits when choosing their abatement targets. In the following, we discuss both cases (revenue- and profit-maximization).

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[6] Formally, the approach with marginal abatement cost curves corresponds to a partial equilibrium modeling framework where the carbon market is analyzed in isolation. General equilibrium and terms-of-trade effects of changes in the carbon price p are, thus, excluded from the analysis. See e.g. Goulder and Mathai (2000).

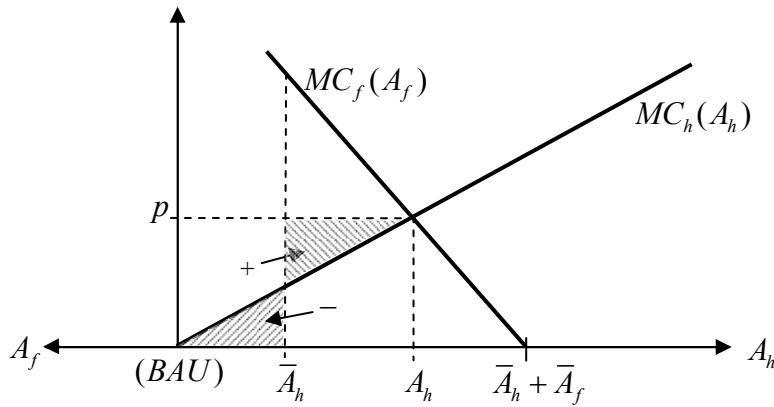Figure 3: Home's profits from emissions trading (linear MACs)

Figure 3 shows home's profits from emissions trading. Home's profit is the area indicated by the "+" sign, net of the area with the "−" sign, because the area under the marginal abatement cost curve reflects the total abatement costs that must be subtracted from the revenues.

Formally, let α be the slope of home's, and let β be the slope of foreign's marginal abatement cost curve (assuming linearity):

$$MC_h(A_h) = \alpha A_h \quad , \quad MC_f(A_f) = \beta A_f \tag{2}$$

If the region "foreign" consists of several countries, then the slope β is derived by adding the individual MACs of these countries horizontally: $\beta \equiv \left(\frac{1}{\beta_1} + \frac{1}{\beta_2} + ... \right)^{-1}$. This implies that the *combined* MAC of several countries is always less steep than any of their individual MACs. Note, that this formula is also used when some of the countries included in "foreign" do not trade permits but sell offsets.[7] These countries do not contribute to foreign's reduction target $\overline{A}_f$, but reduce the slope of foreign's combined MAC β. We obtain the following result:[8]

Proposition 1:

Given linearity of the marginal abatement cost curves, if $\alpha < \beta$, home contributes to climate stabilization ($\overline{A}_h > 0$) if it pursues a revenue-maximization strategy. If home seeks to maximize profits, it prefers to produce hot air ($\overline{A}_h < 0$).

Intuitively, if home seeks to maximize its revenues from selling permits, a binding emissions reduction target is adopted in order to raise the price of certificates. If home seeks to

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[7] Offsets are defined as sellable reductions vis-à-vis a predefined baseline, from countries that are not subject to binding emissions targets (like, but not necessarily equal to the Kyoto CDM). Thus, offsets in this paper always mean 'international offsets', while domestic offset potentials are incorporated in countries' national MAC.
[8] Proofs are relegated to the Appendix.

maximize profits, the optimal abatement target is always lower, as the marginal abatement costs are rising. Under linearity, this effect is so strong that $\bar{A}_h$ becomes negative.[9]

Foreign's target depends on home's target:

The European Union has announced an emissions reduction target of 20 percent (relative to the base year 1990), but is willing to reduce emissions by up to 30 percent if other major emitters also reduce their emissions substantially. The commitment of the EU to positively respond to ambitious reduction targets of other countries may give these countries an additional incentive to lower their emissions. Formally, suppose foreign's abatement target $\bar{A}_f$ consists of a minimum reduction target $\tilde{A}_f$ (independent of home's target), plus an additional term that increases linearly in home's abatement target:

$$\bar{A}_f(\bar{A}_h) = \tilde{A}_f + \gamma \bar{A}_h \tag{3}$$

The parameter γ captures the 'responsiveness' of foreign's target with respect to changes in home's target. As before, we focus on the case with linear MACs.

Proposition 2:

If foreign's abatement target depends on home's target, and home seeks to maximize the profits from trading permits, then home contributes to climate stabilization ($\bar{A}_h > 0$) if foreign's reduction target is sufficiently responsive to home's target ($\gamma > \alpha / \beta$).

Proposition 2 indicates that the EU's commitment to choose a more ambitious reduction target when other countries also choose a lower cap, can trigger higher reductions by these countries.[10] Intuitively, if home chooses a lower cap, it induces upwards pressure on the price of certificates. If foreign responds to this by an even more ambitious reduction target, then home's effect on the permit price is amplified.

Positive valuation of climate stability:

The analysis so far showed that even when home's policy maker does not have a positive valuation for climate stability, home may nevertheless adopt a binding emissions reduction

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[9] When the MACs are non-linear, a voluntary contribution to climate stabilization can be obtained also in the profit maximization case. This is e.g. the case for quadratic MACs (not shown). Böhringer and Löschel (2003) use MACs of the following (more general) type: $MC(A) = \alpha A^{\beta}$.

[10] Proposition 2 focuses on the profit-maximization case to demonstrate that the negative result of Proposition 1 (no contribution to climate stabilization under profit-maximization), is no longer valid when $\gamma > 0$.

target. However, as most countries will be seriously affected by climate change, their valuation for climate stabilization should be positive. In the following, the above model is, thus, extended to incorporate home's willingness-to-pay for greenhouse gas reductions.

For simplicity, we assume that home's valuation of reduced greenhouse gas emissions is *linear* in the amount of reduced emissions. Home's valuation per ton of CO2e avoided is denoted by v_h. The assumption of linearity seems plausible because we consider only one trading period (from 2013 to 2020), while climate protection requires that the total concentration of greenhouse gases in the atmosphere is stabilized in the long run. Hence, it is not crucial whether a ton of CO2e is abated in this trading period or in a future period. What matters is that an emissions path is reached that limits the cumulated emissions over a longer time horizon (Meinshausen et al., 2009). Hence, the valuation per ton of reduced emissions within a trading period should be (roughly) constant. Differences across countries may reflect different attitudes towards the risks of climate change, or differences in their approaches to climate stabilization. E.g., a relatively low valuation today may simply reflect a strategy with more ambitious reduction targets in the more distant future, and less ambitious targets in the nearer future.[11] Home's *welfare* from emissions trading is defined as follows:

$$W_h = p(A_h - \overline{A}_h) - C_h(A_h) + v_h \overline{A}_h (1 + \gamma) \tag{4}$$

, where $p(A_h - \overline{A}_h)$ is home's revenue from trading permits (negative if home is buyer), $C_h(A_h)$ are the abatement costs, and $v_h \overline{A}_h (1 + \gamma)$ is home's valuation of reduced emissions (as before, we allow foreign's abatement target to respond to home's target).

Home's optimal abatement target is given by (see the Appendix):

$$\overline{A}_h = v_h \cdot \frac{(\frac{1}{\alpha} + \frac{1}{\beta})^2}{\frac{1-\gamma}{\alpha} + \frac{2}{\beta}} + \frac{\tilde{A}_f}{1 + \gamma} \cdot \frac{\frac{\gamma}{\alpha} - \frac{1}{\beta}}{\frac{1-\gamma}{\alpha} + \frac{2}{\beta}} \tag{5}$$

, where β stands for the slope of foreign's combined MAC, which includes supply from countries that sell offsets. The fact that β becomes smaller when more countries join a trading scheme has an important implication for home's incentives to adopt a binding reduction target. If foreign's MAC is relatively flat compared to home's MAC, then home's influence on the permit price is weak and $\overline{A}_h$ is likely to become negative unless v_h is sufficiently large. Hence, home's incentives to contribute to global greenhouse gas reductions depend on the total size of the trading scheme, *and* on its valuation for climate stability.

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[11] See Goulder and Mathai (2000) for a discussion of the optimal timing of emissions reductions under technological progress.

Autarky:

We have analyzed so far how a welfare-maximizing country sets its emissions target optimally in an international trading scheme. Given a positive valuation for climate stability, however, the country will also reduce its emissions (relative to BAU) in a situation of autarky, where it can invest only in domestic abatement projects without trading permits. This is the benchmark case against which we shall compare the benefits of emissions trading. If the country's welfare is significantly higher under emissions trading than under autarky, then the adoption of a legally binding emissions target is likely to be in the country's own interest, as a necessary requirement for participation in the trading scheme.

Home's welfare under autarky is given by: $W_h = v_h \bar{A}_h - C_h(\bar{A}_h)$, where $\bar{A}_h$ is the country's reduction target (relative to BAU), and the actual abatement A_h is equal to this.[12] Assuming that the marginal abatement cost function is given by $MC_h(A_h) = \alpha A_h$ as before, the maximization of W_h over $\bar{A}_h$ yields an optimal reduction target of: $\bar{A}_h = v_h / \alpha$. The resulting welfare under autarky is given by: $W_h = v_h^2 / 2\alpha$. The net *surplus* S_h of emissions trading is, then, defined as welfare under trading minus welfare under autarky.

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[12] We assume that home does not accept a binding emissions target when it chooses the autarky-option. Therefore, foreign's reduction target does not react to changes in home's abatement efforts.

3. Numerical analysis

In this section, we apply the results of Section 2 using empirical data, and analyze whether China may benefit from adopting a binding emissions target.

Business-as-usual (BAU) emissions and current reduction pledges:

Figure 4 shows greenhouse gas emissions data for 1990, 2005, and estimates of BAU emissions for the year 2020. For each country or region (EU, USA, China), the Figure also shows the emissions that correspond to the announced reduction target.

Figure 4: GHG emissions
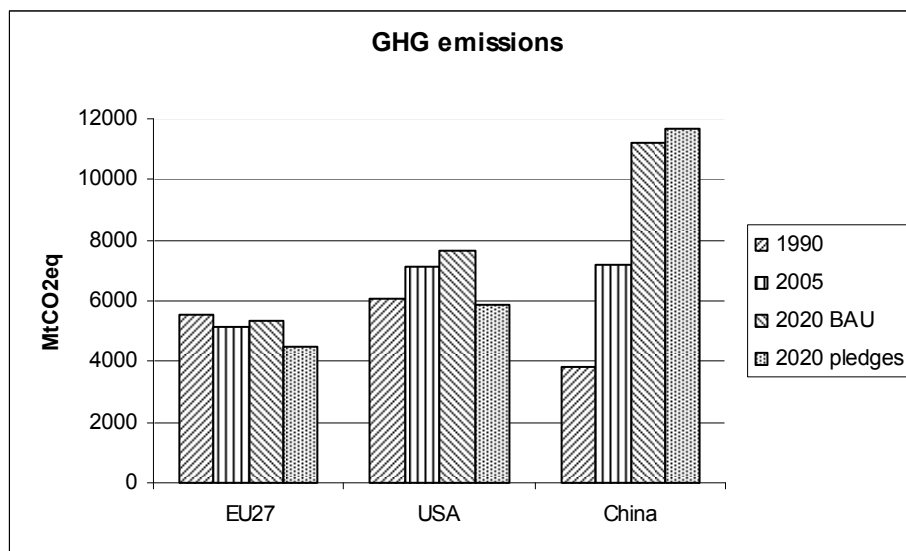
Sources: UNFCCC GHG database for USA and EU past emissions, World Resource Institute CAIT database for China's past emissions, Clapp et al. (2009) Tables 7 and 10 (average value) for EU and USA 2020 projection. The 2020 projection for China was derived by taking the mean of the fossil CO2 projections from IEA (2009) and EIA (2009), and adding a constant share of non-CO2 GHG emissions interpolated from past emissions. All data without LULUCF.

The EU's target is to reduce emissions by 20% relative to the base year 1990, the USA's target is to reduce GHG emissions by 17% relative to 2005, while China announced to cut the carbon intensity of its economy by 40-45% by 2020, relative to 2005 (in the Figure, we use 42.5 percent). In absolute values, the numbers imply a reduction in 2020 of 2.1 GtCO2e and 1.2 GtCO2e below BAU emissions for the USA and the EU, respectively (1.8 GtCO2e for the EU if it implements -30%).[13] For China, the graph shows that a cut in carbon intensity by 42.5% in 2020 does *not* lead to a reduction in GHG emissions (compared to the BAU

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[13] With expected USA BAU emissions of 7.65 GtCO2e in 2020, a reduction of 17% below the 7.11 GtCO2e in 2005 requires a net reduction of 2.1 GtCO2e. With the EU BAU emissions expected to be 5.34 GtCO2e in 2020, a reduction by 20% below the 1990 base-year emissions of 5.56 GtCO2e translates into a net reduction of 1.2 GtCO2e. If the reduction target is raised to -30%, abatement raises accordingly to 1.8 GtCO2e.

projection). The reason for this somewhat surprising result is that recent BAU projections already include existing efforts by the Chinese government to reduce emissions, e.g. energy efficiency improvements and renewable energy expansion.[14] Overall, these efforts are expected to reduce the carbon intensity of China's economy by more than 42.5 percent, so China's recent announcement does not entail any *additional* reductions in GHG emissions.

Estimated marginal abatement costs:

In the following, we use a linear approximation of recent estimates of marginal abatement cost curves in order to derive values for the slopes embedded in the theoretical model of Section 2. In an OECD study, Clapp et al. (2009) compare results from various models. We believe that the average of these results yields a plausible estimate.[15] Using the results from the OECD study, we obtain the following estimates for the slope of the USA's and the EU's MAC: $\beta_{USA} = 24$, and $\beta_{EU} = 42$.[16] The OECD study does not contain data for China. Various estimates of China's MAC found in the literature suggest that a plausible assumption is that its slope α is about 1/2 the slope of the USA's MAC.[17] Hence, we set $\alpha = 12$.

To estimate the EU's and the USA's valuation of reduced emissions (see below), we need to include offset markets into our analysis, as these affect the slopes of their MACs. Unfortunately, MACs for offset markets are hard to quantify. They depend (among other things) on the stringency of the additionality requirements imposed by the countries that buy the offsets. Therefore, we *set* the parameters that represent the slope of MACs of the offset markets, rather than to calibrate them.[18] In case of the USA's offset market, we believe that 1/2 the slope of the USA's MAC may be a useful starting point, as the USA plan to allow for a wide range of offset mechanisms.[19] Hence, we assume $\beta_{offset}^{USA} = 12$ for the USA's offset

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[14] See, e.g. the WRI 'Fact Sheet Energy and Climate Policy Action in China' from June 2009. Available online at http://www.wri.org/stories/2009/06/fact-sheet-energy-and-climate-policy-action-china-update

[15] The OECD study estimates the amount of emissions reductions achieved at a carbon price of 50 $/tCO2e. We use the shown median of these values to derive the slope of the country's MAC.

[16] Throughout this paper, we use the following unit for the slope of a MAC: $1000 US\$ / (MtCO2e)^2$.

[17] Hanaoka *et al.* (2008) find (using AIM models) higher absolute values for the slope of the EU's, the USA's and China's MAC. However, the relation between the slopes is similar. In particular, the slope of China's MAC is about 1/2 the slope of the USA's MAC. Similarly, using the EPPA model, Morris *et al.* (2008) estimate that (under a linear approximation) the year 2020 slope of the MAC of China is about 1/2 of the slope of the US's MAC for emission reductions of at most 2 GtCO2e, after which the slopes become of similar order of magnitude. A similar picture emerges from a bottom-up study of Chinese emission reduction options (CCAP 2006). Contrasting results are shown by Chen (2005), based on MARKAL modeling.

[18] For simplicity, we assume that each country (EU and USA) has its own offset market, which is independent of the offset market of the other country. Hence, the EU and the USA do not compete for the same offsets, and we rule out what is sometimes referred to (Flachsland et al. 2009) as "indirect linking", i.e. an equalization of carbon prices via offset markets.

[19] According to the US EPA (EPA, 2009), international offsets and set-asides are expected to generate a significant part of the overall reduction effort: in fact, in 2020 about 50% of all US abatement would be achieved

market. This implies that the slope of the *combined* MAC of the USA and its offset market equals $\beta = \left(\frac{1}{24} + \frac{1}{12} \right)^{-1} = 8$, hence, only 1/3 of the original value. This strong variation in the slope of the USA's MAC may overstate the possibilities to replace domestic reductions by using offsets, but can be seen as a sensitivity analysis for the robustness of our results (see below). Similarly, we estimate the slope of the MAC of those countries that sell offsets to the EU to be 1/2 the slope of the EU's MAC. This reflects the notion that the EU is likely to set higher standards for offsets, and may impose stricter bounds on their accreditation. Overall, this restricts the supply of offsets, which is reflected in a steeper MAC. Hence, we obtain for the slope of the EU's offset market: $\beta_{offset}^{EU} = 21$, and the slope of the combined MAC (EU + offset market): $\beta = 14$ (also 1/3 of the original value). If our estimated slopes are too low, then the actual offset possibilities are more limited than we assume. As a result, we would *underestimate* China's valuation of GHG reductions (see below), but this does not affect our main result, namely that China can benefit from adopting a binding emissions target.

Countries' valuation of GHG abatement:

In order to compute an optimal reduction target under the assumption of welfare maximization, an estimate of China's valuation of reduced GHG emissions is required. Although this valuation can not be observed directly, it may be revealed by climate policies adopted by the government. However, our data on China's BAU emissions and the intensity target can *not* be used for this purpose, because with policy emissions in 2020 larger than BAU emissions, we would obtain a *negative* valuation of climate stabilization, which does not seem plausible. To circumvent this problem, we use the following indirect approach: We first estimate the USA's and the EU's valuation of reduced emissions revealed by their announced reduction targets. Then we scale the result using China's projected GDP in 2020 to estimate China's valuation per ton of CO2e avoided.[20]

The estimate of the EU's and the USA's valuation of reduced emissions is derived by assuming that their reduction targets correctly reflect their valuation per ton of CO2e avoided, when each of these countries abates domestically, and in addition, has access to an offset market for emissions. At this stage, the inclusion of an offset market is important, because it reduces the abatement costs substantially. When the EU and the USA announced their targets,

by means of international offsets, corresponding to roughly 1 GtCO2e. Without this possibility, marginal abatement costs were expected to be almost twice as high (*ibid*).

[20] This approach yields a consistent estimate of China's valuation of reduced emissions under the simplifying assumption that China's vulnerability to climate damages per unit of GDP is (roughly) as high as the average of the EU's and the USA's vulnerability.

they clearly foresaw the possibility of including offsets in the total reduction effort.[21] Therefore, the exclusion of offsets would lead to an overestimation of the valuation of greenhouse gas reductions. E.g., under autarky (when only domestic reductions are possible), the EU's abatement target of -20% would require a carbon price of about 50 US$/tCO2e.[22] A similar result is obtained for the USA using the -17% target.[23] When offsets are included, the revealed valuations of reduced emissions are lower (see below).

To derive an expression for the valuation v_h, use (5), and set γ and $\tilde{A}_f$ to zero. This yields:

$$v_h = \overline{A}_h (\tfrac{1}{\alpha} + \tfrac{2}{\beta}) \big/ (\tfrac{1}{\alpha} + \tfrac{1}{\beta})^2 \qquad (6)$$

, where α is the slope of the MAC of the country whose valuation v_h is estimated using the country's reduction target $\overline{A}_h$, and β is the slope of the MAC of the offset market. Applying this formula, we obtain an (almost) identical estimate for the valuation of reduced emissions for the USA and the EU: $v_{USA} \cong v_{EU} \cong 28\ US\$/tCO2e$. Hence, the USA's and the EU's reduction targets reveal similar valuations per ton of CO2e avoided. Note, that these valuations lie well within the range of estimated marginal damage costs of CO2 emissions from a large number of studies.[24]

Let us now scale the EU's and the USA's valuation per ton of avoided emissions using China's GDP, to derive an estimate of China's valuation.[25] An upper estimate is that in 2020, China's GDP will be of similar magnitude as the USA's GDP.[26] As an upper bound, let us, thus, assume that China's valuation of reduced emissions is equal to the USA's and the EU's revealed valuation, hence: $v_{China} = 28\ US\$/tCO2e$. However, for various reasons, Chinese policy makers may attach less weight to climate stabilization than implied by our estimate. As a sensitivity analysis, we, therefore, vary this valuation and assume as a lower estimate that

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[21] See, e.g., the US Environmental Protection Agency's analysis of the Waxman-Markey proposal (EPA, 2009).

[22] Given the slope of the EU's MAC ($p = \beta_{EU} \overline{A}_{EU}$; see Section 2). Under autarky, the carbon price reflects a country's valuation per ton of reduced emissions when all reductions are achieved via the price mechanism.

[23] Given the estimated MACs of the EU and the USA, a price of 50 $/tCO2e induces the EU to abate about 1.2, and the USA 2.1 GtCO2e. These are the also the net reductions (below 2020 BAU) required for the EU to meet its -20%, and for the USA to meets its -17% target.

[24] Tol (2005) gathers the results from 28 published studies and constructs a combined probability density function. The author finds that: "if all studies are combined, the mode is $2/tC, the median $14/tC, the mean $93/tC, and the 95 percentile $350/tC". Our estimate for the EU and USA corresponds to $103/tC (in 2005US$), close to the mean value. A further update is provided in Tol (2008).

[25] This scaling is necessary because obviously a country with a low GDP finds it more difficult to pay a given amount of money for reducing emissions than a country with a higher GDP.

[26] The USA's GDP in 2020 is projected to be 17.5 trillion (in 2005 US$), and the EU's around 19.5 in market exchange rates (MER), or 18.8 in PPP. China's GDP is estimated to be 16.9 trillion in 2020 in PPP, and 7.1 in MER (EIA, 2009). For a discussion of when to use MER and PPP, see also den Elzen et al. (2005).

China's valuation per ton of CO2e avoided is only 1/3 of the EU's and the USA's valuation, hence: $v_{China} = 9.33\ US\$/tCO2e$.

Results:

The main results of our numerical analysis are summarized in Table 1, which shows China's optimal reduction target and the resulting surplus resp. revenue for various cases.

Table 1: Estimation of China's optimal reduction target (various cases)

China establishes and links its emissions trading scheme with:	Slope of foreign's combined MAC, in $\dfrac{1000US\$}{(MtCO2eq)^2}$	Foreign's min. reduction target $\tilde{A}_f$ (red. below BAU in 2020)	China's opt. red. target $\overline{A}_h$ under revenue max., and revenue R_h	Target $\overline{A}_h$ under welfare max., and surplus S_h; lower v_{China}	Target $\overline{A}_h$ under welfare max., and surplus S_h; higher v_{China}
EU-ETS ($\gamma = 0$)	42	1.2 GtCO2e	1.5 GtCO2e 15 Bil. US$	0.6 GtCO2e 3.7 Bil. US$	2.2 GtCO2e 1.1 Bil. US$
EU-ETS ($\gamma = 0$) + offset market	14	1.2 GtCO2e	0.1 GtCO2e 5.0 Bil. US$	0.6 GtCO2e 0.6 Bil. US$	2.6 GtCO2e 1.4 Bil. US$
EU-ETS ($\gamma = 0.3$) + offset market	14	1.2 GtCO2e	0.6 GtCO2e 6.0 Bil. US$	0.9 GtCO2e 3.3 Bil. US$	3.1 GtCO2e 23 Bil. US$
US-ETS	24	2.1 GtCO2e	1.1 GtCO2e 26 Bil. US$	0.3 GtCO2e 8.8 Bil. US$	2.1 GtCO2e 2.6 Bil. US$
US-ETS + offset market	8	2.1 GtCO2e	-0.4 GtCO2e 8.8 Bil. US$	0.4 GtCO2e 1.3 Bil. US$	2.9 GtCO2e 2.9 Bil. US$
EU-ETS + US-ETS	15.3	3.3 GtCO2e	0.5 GtCO2e 42 Bil. US$	0.0 GtCO2e 17 Bil. US$	1.9 GtCO2e 5.0 Bil. US$
EU-ETS + US-ETS + offset market	6.7	3.3 GtCO2e	-0.7 GtCO2e 18 Bil. US$	0.3 GtCO2e 4.8 Bil. US$	2.7 GtCO2e 1.0 Bil. US$

The results in Table 1 refer to the following cases: China establishes and links its emissions trading scheme (i) only with the EU-ETS, (ii) only with a (to be established) US-ETS, or (iii) with both of them. We also analyze the effects on China's optimal reduction target when in each of these three cases an additional offset market is included.[27] Alternatively, this can be interpreted as a robustness check (when an offset market is included, the slope of foreign's MAC – relative to China's MAC – is reduced substantially).

Furthermore, for the case where China is linked with the EU-ETS and an offset market, we allow for the EU's emissions cap to positively respond to China's choice of a reduction target. We set the parameter γ that captures the responsiveness to 0.3. Hence, if China commits itself to a GHG emissions reduction of 1 GtCO2e, then the EU's reduction target is raised by an additional 300 MtCO2e. This seems plausible, since the announced conditional raise in the

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[27] When China is linked with the EU-ETS, the US-ETS, and an additional offset market, we assume the slope of the MAC of the offset market is 1/2 the slope of the MAC of the USA.

EU's reduction target from -20% to -30% would require an overall additional abatement of 600 MtCO2e, but the EU's choice will not only depend on China's target.

The table also shows results (column 4) for the case where China adopts a pure revenue-maximization strategy, i.e., where the abatement costs incurred by firms and the damages of climate change are neglected in the policy maker's optimization. This serves mainly as a benchmark, to illustrate the idea that even in the absence of environmental considerations, China may benefit from joining an international emissions trading scheme, and from choosing a cap below BAU emissions.

The first observation from Table 1 is that in most of the cases we consider, China's optimal emissions in 2020 are considerably lower than BAU emissions. Under *revenue maximization*, the highest abatement target (1.5 GtCO2e below BAU) is obtained when China links its trading scheme with the EU-ETS (no offsets). In this case, China trades with a region that faces high abatement costs, and that is committed to reduce its emissions significantly. When an offset market is included, the slope of foreign's combined MAC drops to 1/3 of its original value. This makes it more difficult for China to raise the permit price, so its optimal reduction is lower (100 MtCO2e). However, once the EU's conditional commitment with respect to the reduction targets of other large emitters ($\gamma > 0$) is considered, China's optimal reduction increases to more than 600 MtCO2e. Hence, the EU's conditional commitment can trigger additional contributions to climate stabilization in these countries. When China is linked with the US-ETS + offset market, then China prefers to produce "hot air" under revenue-maximization. Hence, China's abatement target $\overline{A}_h$ becomes negative. The reason for this is that China's MAC is, then, steeper than foreign's combined MAC. The same holds true when China is linked with the EU-ETS + the US-ETS + an additional offset market.

Now consider China's optimal reduction target under *welfare maximization*.[28] Let us first summarize the outcomes under autarky (as a benchmark). In this case, a positive welfare is achieved only through domestic reductions (a binding emissions target is not required). For the larger estimate of v_{China}, China's optimal reduction target under autarky is $\overline{A}_h = 2.3$ GtCO2e, and the resulting welfare is $W_h = 33$ Billion US\$.[29] For the lower v_{China}, China's reduction target under autarky is $\overline{A}_h = 0.8$ GtCO2e, and welfare is $W_h = 3.6$ Billion US\$.

When China joins an international emissions trading scheme, surplus[30] can be created through two channels: 1. higher reductions of total GHG emissions, and 2. profits from trading

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[28] Recall: welfare = revenues – abatement costs + total valuation of reduced emissions.
[29] To derive these values, see Section 2 (autarky case).
[30] Recall: surplus of emissions trading = additional welfare relative to autarky.

permits. These motives explain why, in a given situation, China adopts a more or less ambitious reduction target, and why it can achieve a higher or a lower surplus from trading permits. Let us illustrate this by comparing different situations.

First consider the case where China's is linked with the EU-ETS (no offsets), hence, to a region that faces high abatement costs. Under the lower v_{China}, China's reduction target (0.6 GtCO2e) is comparable to the one under autarky (0.8 GtCO2e), but the surplus from trading is substantial (3.7 Billion US$). This surplus stems entirely from selling permits, and the reason why China does not choose a higher cap (in order to sell more permits) is that this would lead to a lower price. Under the higher v_{China}, China's decision making is mainly governed by environmental considerations (note: welfare under autarky is already 33 Billion US$). Hence, China's optimal cap (2.2 GtCO2e) is only slightly below the optimal reduction under autarky (2.3 GtCO2e), and the surplus from trading is actually lower than under the lower v_{China}.

Compare this with a situation where China is linked with a US-ETS + offset market. Under the larger v_{China}, China can reap substantial benefits from trading permits (the surplus is 2.9 Billion US$). These benefits stem entirely from China's additional contribution to global emissions reductions (China's reduction target is 2.9 GtCO2e, and exceeds the target under autarky: 2.3 GtCO2e). China's profits from trading permits are actually negative in this case, as it becomes a buyer of permits. However, the large benefits of climate stabilization more than compensate China for these losses. This is due to the fact that China trades with a region that (on aggregate) faces lower abatement costs (the slope of foreign's MAC is 8, the slope of China's MAC is 12). Under the lower v_{China}, the situation is reversed: China now reaps some positive profits by selling permits, but overall, the surplus from trading is lower than under the higher v_{China} (1.3 Billion US$ instead of 2.9). Let us summarize:

- Under the lower valuation v_{China}, revenues dominate China's decision making. Therefore, China tends to choose more ambitious reduction targets when it is linked with regions that face *high* abatement costs, in order to raise the price of permits. China's surplus (relative to autarky) is higher when foreign has an ambitious reduction target, because this allows China to sell more permits at a high price.

- Under the higher valuation v_{China}, China's decision making is governed by environmental considerations. Its contribution to global GHG reductions tends to be larger when it is linked with a region that faces *low* abatement costs.[31] China's surplus from trading is

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[31] This intuition is confirmed by e.g. comparing the effect of excluding the offset market when China trades with the USA: China's optimal reduction target, then, drops from 2.9 to 2.1 GtCO2e.

higher when foreign has a low reduction target. China, then, uses the trading scheme to reduce its abatement costs and becomes a buyer of permits.

4. Conclusion and discussion

This paper shows that for a wide range of cases China could benefit from adopting a binding emissions target, since it would allow China to join an international emissions trading scheme. If China is linked to a country or region (such as the EU) that faces high abatement costs, it can generate substantial revenues from selling permits. Emissions trading can, thus, offer the possibility of selling low-cost abatement options to countries with a high willingness-to-pay. Our numerical results confirm this presumption. Conversely, if China is linked to a large emissions trading scheme characterized by low abatement costs, such as a (to be established) US-ETS with an outside offset market, then China can become a buyer of permits. However, also in this case, trade in permits allows China to increase its surplus, via a larger contribution to global emissions reductions, compared to a situation of autarky.

The results in this paper were derived under the simplifying assumption that the USA and the EU have already fixed their reduction targets, and that China tries to find its best response to these targets. Hence, instead of computing a Nash equilibrium, the targets of the other countries were treated as exogenous. Differences in countries' approaches to address the problem of climate change may make it problematic to apply a non-cooperative equilibrium concept. E.g., the EU's commitment to reduce emissions by 30% rather than 20% if other large emitters also adopt ambitious targets clearly reveals the EU's willingness to cooperate in averting climate change.

The choice of emissions trading as a tool to mitigate climate change generally bears the risk of 'gaming' in terms of the involved countries' reduction targets. While in some cases this may actually improve the willingness to contribute to climate protection, in general it implies the risk of compromising the overall reduction target (Helm, 2003). Hence, instead of relying on individual countries' voluntary contributions to climate protection, a more promising approach may be to fix an upper bound of the total amount of world-wide emissions until 2020 and thereafter, in order to prevent the world from dangerous or catastrophic climate change (Meinshausen *et al.*, 2009). In a second step, a formula could be defined and agreed upon that allocates this quantity to countries according to, e.g., their GDP, historic emissions,

and abatement possibilities. This two-stage approach may reduce the risks of 'gaming' in the countries' choice of individual reduction targets. [32]

Although this paper highlighted benefits of an international emissions trading scheme, readers should keep in mind that a well-designed carbon tax, combined with transfers (covered e.g. by part of the carbon tax revenues), may perform equally well from an economic perspective (see, e.g., Nordhaus 2007). Given the estimated MACs used in this paper, a carbon tax of 50 US$/tCO2e would be sufficient for the EU and the USA to reach their announced reduction targets domestically. Under a global carbon tax, a lower rate may be sufficient to curb total emissions.

References:

Böhringer, C.; Löschel, A. (2003). Market power and hot air in international emissions trading: the impacts of US withdrawal from the Kyoto Protocol. *Applied Economics*, 35, p.651-663.

Carbone, J.C.; Helm, C.; Rutherfort, T.F. (2009). The case for international emission trade in the absence of cooperative climate policy. *Journal of Environmental Economics and Management* 58 (3), p.266-280.

CCAP (2006). Greenhouse Gas Mitigation in Brazil, China and India: Scenarios and Opportunities through 2025. Center for Clean Air Policy. Washington, DC. Available online at http://www.ccap.org/docs/resources/62/CCAP_Developing_Country_Project-Synthesis_Report_Nov_2006_.pdf

Chen, W. (2005). The costs of mitigating carbon emissions in China: findings from China MARKAL-MACRO modeling. *Energy Policy* 33, p.885-896.

Clapp, C., K. Karousakis, B. Buchner and J. Chateau (2009). National and Sectoral GHG Mitigation Potential: A Comparison Across Models. OECD/IEA, Paris, France. Available online at http://www.oecd.org/dataoecd/42/33/44050733.pdf

den Elzen, M.G.J., Lucas, P., von Vuuren, D.P. (2005). Abatement costs of post-Kyoto climate regimes, *Energy Policy* 33, p.2138-2151.

EIA (2009). International energy outlook 2005. Energy Information Administration, Washington, D.C., USA.

EPA (2009). Analysis of the American Clean Energy and Security Act of 2009. United States Environmental Protection Agency. Available online at http://epa.gov/climatechange/economics/pdfs/HR2454_Analysis.pdf

Flachsland, C., Marschinski, R., Edenhofer O. (2009). Global Trading versus Linking: Architectures for International Emissions Trading. *Energy Policy* 37 (5), p.1637-1647.

Goulder, L.H., Mathai, K. (2000) Optimal CO2 abatement in the presence of induced technological change. *Journal of Environmental Economics and Management* 39, p.1–38.

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[32] Such a two-stage fixed-budget approach has e.g. been advanced by the German Advisory Council on Global Change (WBGU, 2009).

Hahn, R.W. (1984). Market Power and Transferable Property Rights. *Quarterly Journal of Economics*, 99, p.753-765.

Hanaoka, T., O. Akashi, Y. Kanamori, T. Hasegawa, G. Hibino, K. Fujiwara, M. Kainuma, and Y. Matsuoka (2008) Global Greenhouse Gas Emissions Reduction Potentials and Mitigation Costs in 2020 - Methodology and Results. CGER-Report. Center for Global Environmental Research, National Institute for Environmental Studies, Japan

Helm, C. (2003) International emissions trading with endogenous allowance choices. *Journal of Public Economics*, 87, p.2737-2747

IEA (2009) How the Energy Sector Can Deliver on a Climate Agreement in Copenhagen. Special early excerpt from the World Energy Outlook 2009. International Energy Agency/OECD, Paris, France. Available online at http://www.iea.org/weo/docs/weo2009/climate_change_excerpt.pdf

Lutter, R. (2000) Developing countries' greenhouse emissions: Uncertainty and implications for Participation in the Kyoto Protocol. *Energy Journal*, 21, p.93-120.

Meinshausen, M., Meinshausen, N., Hare1, W., Raper, S.C.B., Frieler, K., Knutti, R., Frame, D.J., Allen, M.R. (2009) Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature*, 458, p.1158-1163

Morris, J, Paltsev, S., and Reilly, J. (2008). Marginal Abatement Costs and Marginal Welfare Costs for Greenhouse Gas Emissions Reductions: Results from the EPPA Model. MIT Joint Program on the Science and Policy of Global Change, Report No. 164

Nordhaus, W.D. (2007) To Tax or Not to Tax: Alternative Approaches to Slowing Global Warming. *Review of Environmental Economics and Policy*, 2007 1(1), p.26-44

Sterk, W., Kruger, J. (2009) Establishing a transatlantic carbon market. *Climate Policy*, 9, p.389-401

Tol, R.S.J. (2005) The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties. *Energy Policy*, 33, p.2064-2074

Tol, R.S.J. (2008) The Social Cost of Carbon: Trends, Outliers and Catastrophes. *Economics*, Vol. 2, 2008-25. http://www.economics-ejournal.org/economics/journalarticles/2008-25

WBGU (2009) Solving the Climate Dilemma: The Budget Approach. Special report of the German Advisory Council on Global Change (WBGU). Berlin, Germany. Available online at http://www.wbgu.de/wbgu_sn2009_en.pdf

Appendix:

<u>Proof of Proposition 1</u>:

The actual abatement of home and foreign is equal to the sum of the target abatement levels:

$$A_h + A_f = \overline{A}_h + \overline{A}_f \tag{7}$$

Home's revenue is, thus: $R_h = p(A_h - \overline{A}_h) = p(\overline{A}_f - A_f)$. With linear MACs (see (2)), (1) yields: $A_h(p) = p/\alpha$ and $A_f(p) = p/\beta$. Replacing A_f by p/β, we obtain: $R_h(p) = p(\overline{A}_f - p/\beta)$. Maximize over p to find:

$$p = \beta \overline{A}_f / 2 \tag{8}$$

To obtain home's optimal abatement target, solve (7) for $\overline{A}_h$, replace A_h and A_f by, respectively, p/α and p/β, and use (8) to obtain after rearranging:

$$\overline{A}_h = \frac{\beta - \alpha}{2\alpha} \overline{A}_f \tag{9}$$

This is greater than zero (voluntary contribution to climate stabilization) if $\beta > \alpha$.

To show the second part of the Proposition (profit maximization), follow the same steps, but use the target function: $\pi_h = R_h - \alpha A_h^2 / 2$, where $\alpha A_h^2 / 2$ is home's total abatement cost (it corresponds to the MAC: $MC_h(A_h) = \alpha A_h$). This yields:

$$\overline{A}_h = -\frac{\alpha}{2\alpha + \beta} \overline{A}_f < 0 \tag{10}$$

, which completes the proof.   *Q.E.D.*

<u>Proof of Proposition 2</u>:

The timing is as follows: first, foreign announces the minimum reduction target $\tilde{A}_f$, and the responsiveness γ of its total target $\overline{A}_f$ w.r.t. changes in home's target $\overline{A}_h$. Given this information, home chooses $\overline{A}_h$. Finally, $\overline{A}_f$ adjusts according to (3), and the actual abatement levels A_h and A_f are determined by (1). Note, that when home chooses $\overline{A}_h$, foreign's minimum abatement target $\tilde{A}_f$ is already fixed. Hence, all results now depend on $\tilde{A}_f$ and γ. Use (3) in (7) to get:

$$A_h + A_f = (1 + \gamma)\overline{A}_h + \tilde{A}_f \tag{11}$$

Using this modified condition, the rest of the derivation follows same steps as shown in the proof of Proposition 1. For the sake of brevity, we only show the main results.[33] Under profit-maximization, home's optimal abatement target is: $\bar{A}_h = \dfrac{(\beta\gamma - \alpha)\tilde{A}_f}{(1+\gamma)(2\alpha + \beta - \beta\gamma)}$. This is greater than zero if $\gamma > \dfrac{\alpha}{\beta}$, and finite if $\gamma < \dfrac{2\alpha + \beta}{\beta}$ (which we assume is always fulfilled). $Q.E.D.$

Surplus maximization with positive environmental valuation:

Home's target function under welfare maximization is given by (4). Since foreign's abatement target may depend on home's target $\bar{A}_h$ via γ, use (11) instead of (7) (as in the proof of Proposition 2). Otherwise, follow the same steps as in the proof of Proposition 1 to derive home's optimal abatement target. For the sake of brevity, we only show the main results. Home's optimal abatement target under welfare maximization is given by (5) (see the main text). Given this target, we find the following expression for the permit price:

$$p = (\tfrac{1-\gamma}{\alpha} + \tfrac{2}{\beta})^{-1}(\tilde{A}_f + (1+\gamma)(\tfrac{1}{\alpha} + \tfrac{1}{\beta})v_h) \tag{12}$$

, where β is the slope of the combined MAC of foreign.

For comparison, under revenue maximization when foreign's abatement target depends on home's target ($\gamma > 0$), we find for home's optimal abatement target and the permit price:

$$\bar{A}_h = \tfrac{1}{2(1+\gamma)}(\tfrac{1+2\gamma}{\alpha} - \tfrac{1}{\beta})(\tfrac{1}{\beta} - \tfrac{\gamma}{\alpha})^{-1}\tilde{A}_f \tag{13}$$

$$p = \tfrac{1}{2}(\tfrac{1}{\beta} - \tfrac{\gamma}{\alpha})^{-1}\tilde{A}_f \tag{14}$$

Note, that (13) and (14) are equivalent to (9) resp. (8) when $\gamma = 0$.

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[33] A detailed proof can be obtained from the authors upon request.