Efficiency of Emissions Trading between Systems with Absolute and Intensity Targets

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Abstract: Emissions trading is regarded as a crucial instrument for a cost-effective implementation of climate policy. At the same time, the shape of global climate policy after the expiration of the Kyoto Protocol in 2012 is highly uncertain. Intensity targets, which limit the amount of emissions per output, have been proposed as an alternative to Kyoto- style absolute emission targets. In fact, the emergence of a fragmented regime in which one group of countries adopts the former and another group of countries the latter cannot be excluded. The question then arises of whether emissions trading between countries that are not subject to the same type of constraint would lead to an efficient outcome. Within a simple analytical framework, we find that permit trade between a country with an absolute and one with an intensity target never leads to a Pareto efficient equilibrium. Moreover, global emissions increase if the country with the intensity target is a net buyer of permits. We propose an ad valorem tax on traded permits in the intensity based regime, which restores Pareto optimality.

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1. Introduction

A key issue in the current climate policy debate is what kind of follow-up agreement should or could succeed the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC), due to expire in 2012 (e.g. Aldy and Stavins, 2007; Bodansky, 2004; Harvard Project, 2008). As of today, no silver bullet has emerged, and the multitude of circulating proposals, together with the heterogeneity across countries' characteristics and objectives suggests the likely emergence of a fragmented regime, perhaps consisting of one or several coalitions, associated blocks, and free-riders (Biermann et al., 2007; Victor, 2007). For instance, even if the United States remain outside a post-Kyoto accord, individual or groups of US federal states might adopt reduction targets and trade permits with the European Emissions Trading Scheme (ICAP, 2007; Edenhofer et al., 2007). Schmidt et al. (2006) have suggested for China to adopt intensity targets for some of its sectors in order to participate in international permit trade. Moreover, even within a climate coalition there may be differences in how individual countries choose to implement climate policy or what sectors to cover.

Among the competing policy choices, one aspect regards the mechanism by which emission control is implemented. On the one hand there are absolute targets, which require future emissions not to exceed a certain amount of CO2 (or CO2 equivalents). Such targets, also referred to as caps, were adopted by most industrialized countries under the Kyoto Protocol. On the other hand, so called intensity targets set an upper limit on the ratio of emissions per output, often expressed in CO2 per GDP. As the most prominent example, the U.S. administration has adopted such a target in 2002, pledging to reduce greenhouse gases emissions relative to GDP by 18% by 2012 compared with 2002.[1] Also Canada is planning to set up an emissions trading system based on intensity targets (Government of Canada, 2007).

In the literature, the advocates of such intensity targets argue that they reduce cost uncertainty in the face of unknown, but GDP sensitive, business-as-usual emissions (Frankel, 1999; Kolstad, 2005), although this has been questioned by others (Quirion, 2005; Marschinski and Lecocq, 2006). Furthermore, intensity targets supposedly facilitate the participation of developing countries because they do not limit economic growth (Lisowski, 2002).

The focus of this paper, however, is not on the well-researched uncertainty properties of the two mechanisms. In a purely deterministic setting, we analyze emissions trading in a situation in which one country (or block of countries) has adopted intensity targets and the other absolute targets. Does trade in emission permits between these two systems still lead to the same efficient outcome as under a universal cap-and-trade approach?

To our knowledge, little research has been published on this question. Herzog et al. (2006) critically observe that the actual emissions allowance under an intensity target is only known ex-post, i.e. once economic output is known, but see no principal incompatibility for trade between absolute and intensity based systems. Fischer's (2003) contribution is most closely related to our work. In a partial equilibrium two-sector model she analyzes the behavior of two representative firms, one subjected to a rate-based emission policy, the other to a cap-and-trade policy. Somewhat similar to us, she finds that in the absence of cross-price effects permit trade always leads to an expansion of combined emissions.

However, our work differs on two substantial points. First, it pursues a different methodological approach: while Fischer's analysis takes on a micro view and assumes constant marginal production costs, we adopt a macroeconomic production function with decreasing returns to scale, in line with important models employed in the integrated assessment modeling (IAM) community, such as the well known DICE (Nordhaus, 1992) and RICE (Nordhaus and Young, 1996) model. Second, Fischer emphasizes the identification of suitable strategies capable of suppressing the emission-expanding leakage effect. The present article, meanwhile, mainly investigates whether emissions trade between countries (or sectors) with absolute and with intensity target leads to an efficient outcome.

By means of a simple conceptual model of two economies with representative agents and emissions as sole factor of production, we derive three main results: first, cross-system emissions trade leads to increased global emissions, but only if the country with intensity target is a net buyer of permits; otherwise global emissions decrease. Second, cross-system emissions trade always leads to equilibria not satisfying Pareto efficiency. Third, we propose a suitable tax on traded permits that restores Pareto efficiency.

The remaining part of the paper is organized in the following way: the next section introduces the analytical framework. Section 3 contains the main results on free emissions trade between a country with an absolute and one with an intensity target. Section 4 discusses an efficiency restoring tax on traded permits, and Section 5 concludes.

2. Analytical framework

Consider a closed economy consisting of a single representative agent. Let *Y* denote output and *E* emissions. Within our framework we assume that output might be expressed as a function *F* of emissions

$$Y = F(E) \quad , \tag{1}$$

where we restrict the argument *E* to values that do not exceed the business-as-usual (BAU) emissions. We denote BAU values of all variables with a subscript zero, hence $E \leq E_0$. Over this domain, *F* is strictly increasing in *E*, i.e. $F'(E) > 0$ and concave, i.e. $F''(E) < 0$. It will be useful to define a local emissions elasticity of output

$$\varepsilon(E) := \frac{dF(E)}{dE} \bigg/ \frac{F(E)}{E} \tag{2}$$

Within the given domain of *E*, this quantity is always positive and smaller than unity due to the decreasing productivity of emissions (marginal productivity – the numerator – is always smaller than average productivity – the denominator). This is tantamount to saying that in percentages the loss of output due to an emissions reduction will always be smaller than the corresponding reduction of emissions. Moreover, if F takes on the specific form of a power law function, ε will coincide with the exponent, suggesting an interpretation of ε as roughly representing the value share of emissions in the production function.

Next, let γ denote the emission intensity of output, which in the BAU case is given by $\gamma_0 = E_0/Y_0$. It is straightforward to show that the intensity γ increases whenever emissions E increase, and that emissions and intensity are thus linked by a one-to-one relationship.[2]

In this analysis, two types of emission reductions are considered: first absolute targets, which constrain emissions to a given level $\overline{E}$, and, second, intensity targets, which set a maximum intensity of $\overline{\gamma}$. In a deterministic setting with only one economy, absolute and intensity targets are equivalent instruments for the purpose of emission control, since any absolute target can be implemented through an intensity target by choosing

$$\overline{\gamma}(\overline{E}) = \frac{\overline{E}}{F(\overline{E})}, \tag{3}$$

where $\overline{\gamma}(\overline{E})$ denotes what we shall call the equivalent intensity target. However, even though the two mechanisms can in that sense be considered as equivalent, they still differ in their 'mechanics': for instance, reducing emissions by a given percentage will not lead to the same outcome as reducing the emissions intensity by the same percentage. In fact, denoting the relative reduction of the absolute emission level by

$$r := \left(E_0 - \overline{E}\right)/E_0 \tag{4}$$

it can be shown that the equivalent reduction of intensity – i.e. one that yields the same ex-post emission level $\overline{E}$ – should be smaller than r:

$$\frac{\gamma_0 - \bar{\gamma}(\overline{E})}{\gamma_0} = \frac{E_0 / Y_0 - \overline{E} / F(\overline{E})}{E_0 / Y_0} = 1 - \frac{\overline{E}}{E_0} \frac{Y_0}{F(\overline{E})} < r \tag{5}$$

since $Y_0 > F(\overline{E})$. This just reflects the fact that a, say, 10% reduction of intensity would lead to a 10% emission reduction if output remained constant, but actually leads to more than 10% emission reduction when taking into account that diminished output always implies a smaller allocation under the intensity target.

3. Permit trade between cap and intensity system

Consider first an economy where emissions trading is restricted to the domestic arena. As the first proposition shows that whether a certain emissions target is implemented by an absolute or intensity target will make a difference for the equilibrium permit price in the domestic emissions market.

Proposition 1: For a given economy characterized by a production function *F* with local emissions elasticity *ε(E)* smaller than 1, marginal abatement costs – and thus the domestic emissions price in equilibrium – are lower under an absolute cap than under the equivalent intensity target.

Proof: Suppose emission permits Π from outside the economy were available at a price p. In case of an absolute target $\overline{E}$, the equilibrium price p_A at which no permit trade (Π=0) would occur is characterized by the condition

$$\max_{\Pi} \left[Y(\overline{E} + \Pi) - p \;\; \Pi \right] \;\; \Leftrightarrow \;\; \max_{E} \left[F(E) - p \, (E - \overline{E}) \right] \; \Rightarrow \; F'(\overline{E}) = p_A \tag{6}$$

In case of the equivalent intensity target $\bar{\gamma}(\overline{E})$, the no-trade equilibrium price p_I occurs if

$$\max_E \left[F(E) - p\ (E - \bar{\gamma}\ F(E)) \right] \Rightarrow \frac{F'(\bar{E})}{1-\varepsilon(\bar{E})} = p_I \tag{7}$$

is fulfilled. Therefore, it follows that for 0<ε<1 we obtain $p_I > p_A$ □

The interpretation of this result is straightforward: acquiring a permit of 1 ton CO2 allows to expand emissions by just one ton in a system with absolute targets, with an according increase of output. But in the intensity based regime the acquired permit allows a higher level of emissions, leading to a higher level of output, which in turn again leads to a higher level of allowed emissions. In sum, the net increase in output is larger than it would be under absolute targets, and, as a consequence, an agent in the intensity based regime is willing to pay more for an emissions permit than her/his virtual counterpart facing an absolute target. This immediately has the following implication:

Corollary 1: Let there be two countries with identical economies, producing the same perfectly substitutable output. Both are constrained to the same emission level $\bar{E}$, albeit one by means of an absolute target and the other by means of an (equivalent) intensity target. Introducing an international market for emission permits (and no other trade), the two countries will exchange some emission permits, since, according to Proposition 1, domestic prices are different in the pre-trade state. As a consequence, emission levels will diverge.

In fact, it is evident that the country which has adopted the intensity target will buy permits from the country with the absolute target, and that the equilibrium price *p* will settle between $p_A < p < p_I$. Moreover, it is also clear that this trade cannot yield a Pareto efficient allocation of emissions in equilibrium: since we assumed perfect symmetry between the two countries and since Pareto efficiency implies the same marginal productivity of emissions across countries, efficient allocations cannot but have the same level of emissions in both countries.

Nevertheless, in purely economic terms this permit trade is mutually beneficial, i.e. it raises income in both countries. However, this comes at the cost of increased global emissions:

Proposition 2: Under the conditions described in Corollary 1, free permit trade between the two countries leads to an increase of global emissions with respect to the pre-trade state.

Proof: Let Π and Δ denote the change in emissions with respect to autarky of the country with absolute target and intensity target, respectively. Given a permit price p, the countries solve, again respectively

$$\begin{aligned} &\max_{\Pi} \left[F(\overline{E}+\Pi) - p\ \Pi\right] \quad \Rightarrow \quad F'(\overline{E}+\Pi) = p \\ &\max_{\Delta} \left[F(\overline{E}+\Delta) - p\left(\Delta - \left(\overline{\gamma}\ F(\overline{E}+\Delta) - \overline{E}\right)\right)\right] \quad \Rightarrow \quad \frac{F'(\overline{E}+\Delta)}{1-\overline{\gamma}\ F'(\overline{E}+\Delta)} = p \end{aligned} \tag{8}$$

Note that although Π coincides with the amount of traded permits for the country with absolute target, the traded amount of the intensity based system is given not by Δ but instead by $\Delta - \left(\overline{\gamma}\ F(\overline{E}+\Delta) - \overline{E}\right)$, i.e. only by that part of the change in emissions that is not covered by the adjustment of the intensity target. In equilibrium, market clearing requires the net sum of traded permits to be zero, hence

$$\Pi + \left[\Delta - \left(\overline{\gamma}\ F(\overline{E}+\Delta) - \overline{E}\right)\right] \overset{!}{=} 0\ , \tag{9}$$

proving that the net change of global emissions is positive, namely

$$\Pi + \Delta = \overline{\gamma}\ F(\overline{E}+\Delta) - \overline{E} = \overline{E}\left(\frac{F(\overline{E}+\Delta)}{F(\overline{E})} - 1\right) > 0 \qquad \square \tag{10}$$

Thus, the increase in global emissions depends positively on how much the intensity based country expands its output in the course of permit trading. In fact, if we assume the expansion of its emissions to be small with respect to the pre-trade emissions level, we can approximate the percentage increase in global emissions by

$$\frac{\Pi+\Delta}{2\overline{E}}=\frac{\overline{\gamma}\,F(\overline{E}+\Delta)-\overline{E}}{2\overline{E}}\cong\frac{\overline{\gamma}\,F(\overline{E})+\Delta\,\overline{\gamma}\,F'(\overline{E})-\overline{E}}{2\overline{E}}=\frac{1}{2}\,\varepsilon(\overline{E})\,\frac{\Delta}{\overline{E}} \tag{11}$$

which shows that the relative increase becomes significant whenever ε, the emissions elasticity of output, is sufficiently high.

As the next step, we relax the didactically motivated assumption of symmetric countries. The following proposition holds for emissions trade between two arbitrary countries:

Proposition 3: Let there be two countries characterized by output-emissions functions F and G, respectively. The first is limited to emissions $\overline{E}$ by means of an absolute target, the second to an emissions level $\widetilde{E}(\widetilde{\gamma})$ by means of an intensity target $\widetilde{\gamma}$. In this setting, free international permit trade leads to a market equilibrium that is not Pareto optimal, in the sense that the same global emissions level could be reached at lower costs.
Proof: It is common knowledge that for a cost-minimizing implementation of a given global emissions target the marginal productivity of emissions must be equalized across all countries, i.e.

$$F'(\overline{E}+\Pi)\overset{!}{=}G'(\widetilde{E}+\Delta) \quad . \tag{12}$$

However by requiring a unique price p in equilibrium we obtain

$$F'(\overline{E}+\Pi)=\frac{G'(\widetilde{E}+\Delta)}{1-\widetilde{\gamma}\,G'(\widetilde{E}+\Delta)} \quad , \tag{13}$$

by the same argument as in the proof to Proposition 2. For any $\widetilde{\gamma}>0$, Eq.(13) evidently contradicts the efficiency condition given in Eq.(12) since $F'>G'$. □

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.

The generalization of Proposition 2 is immediate.

Proposition 4: Emissions trading between arbitrary 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.

Proof: Let $\overline{E}$ and $\widetilde{E}(\widetilde{\gamma})$ denote the absolute and implied emissions cap, and Π and Δ the change in emissions with respect to autarky of the country with absolute target and intensity target, respectively. Given a permit price *p*, the countries solve

$$\begin{aligned} &\max_{\Pi} \left[F(\overline{E}+\Pi) - p\ \Pi\right] \quad \Rightarrow F'(\overline{E}+\Pi) = p \\ &\max_{\Delta} \left[G(\widetilde{E}+\Delta) - p\,(\widetilde{E}+\Delta-\widetilde{\gamma}\ G(\widetilde{E}+\Delta))\right] \quad \Rightarrow \frac{G'(\widetilde{E}+\Delta)}{1-\widetilde{\gamma}\ G'(\widetilde{E}+\Delta)} = p \end{aligned} \tag{14}$$

Market clearing for permits requires the sum of all traded permits to be zero, hence

$$\Pi + \left[\Delta - \left(\widetilde{\gamma}\ G(\widetilde{E}+\Delta) - \widetilde{E}\right)\right] \overset{!}{=} 0 \ , \tag{15}$$

proving that the net change of global emissions depends only on the sign of Δ

$$\Pi + \Delta = \widetilde{\gamma}\ G(\widetilde{E}+\Delta) - \widetilde{E} = \widetilde{E}\left(\frac{G(\widetilde{E}+\Delta)}{G(\widetilde{E})} - 1\right) > 0 \quad if \quad \Delta > 0 \qquad \square \tag{16}$$

In sum, although both types of targets are equally well equipped to control emissions in autarky, the ‘mechanical’ differences between the two instruments provoke an efficiency breakdown 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. These effects can be explained by an upwardly distorted permit price in the intensity based regime, i.e. the nominal price is higher than the actual marginal abatement costs. To abandon international permit trade completely would not be a desirable solution to this problem, since it is generally viewed as crucial for a cost efficient and thus affordable implementation of climate policy. On the other side, free permit trade between countries – or even sectors – adhering to different mechanisms does not yield a Pareto optimal equilibrium, which is also undesirable. A possible solution, as discussed in next section, is to apply a specific tax on traded permits in the intensity based regime.

4. Application of a tax as corrective policy measure

In the last section it was shown that the distorted domestic permit price lies at the heart of the trade incompatibility between regions with absolute and intensity based targets. It thus seems natural to impose a tax on permit trade in the intensity based regime.

Proposition 5: The correct permit price which reflects the true marginal productivity of emissions is recovered if an ad valorem tax τ of

$$\tau = p\bar{\gamma} / (1 - p\bar{\gamma}) \tag{17}$$

on traded permits is introduced in the country with the intensity target[3] or, alternatively, imposed on it from the outside in form of a tariff.

Proof: From the point of view of a small representative firm, the optimal amount of acquired/sold permits is determined by the optimization problem, now including the tax

$$\max_{\Delta} \left[F(\bar{E} + \Delta) - p\,(1+\tau)\,(\bar{E} + \Delta - \bar{\gamma}\; F(\bar{E} + \Delta)) \right]$$

$$\Rightarrow\; F'(\bar{E} + \Delta) = \frac{p\,(1+\tau)}{1 + p\bar{\gamma}\,(1+\tau)} = \frac{p/(1-p\bar{\gamma})}{1 + \dfrac{p\bar{\gamma}}{(1-p\bar{\gamma})}} = p \qquad \square \tag{18}$$

In effect, the tax modifies the permit price p and makes it appear to firms as $\hat{p}$

$$\hat{p} = p(1+\tau) = p\left(1+\frac{p\bar{\gamma}}{1-p\bar{\gamma}}\right) = \frac{p}{1-p\bar{\gamma}} \tag{19}$$

i.e. it becomes somewhat inflated. However, the correction will likely be small for typical 'real' economies: assuming an emission permit price of 30 USD/tCO2, and taking current CO2 intensities[4] of 0.55 kgCO2/USD for the United States, 0.36 kgCO2/USD for the EU25, and 0.73 kgCO2/USD for China, the term $p\bar{\gamma}$ takes on a value of 0.017, 0.011, and 0.022, respectively, making it reasonable to approximate $\hat{p} \cong p\,(1+p\bar{\gamma})$, and thus suggesting a tax correction of the order of magnitude of a few percent for the aggregate economy.

However, in light of the before mentioned concept of sector-specific intensity targets (Schmidt et al., 2006), the tax might be significantly higher. For example, the emission intensity in some energy intensive sectors, such as electricity, cement or steel production, is up to one order of magnitude higher (for China, see, Chang et al., 2003, p.145), indicating that the optimal value of a sector-specific ad valorem tax correction could be 10 or even 20 percent for these sectors.

Another rule-of-thumb for the optimal tax level is derived by assuming that the amount of traded permits Δ remains small compared to the initial cap $\bar{E}$. We then have $F'(\bar{E}+\Delta) \cong F'(\bar{E}) + \Delta F''(\bar{E})$, and, in equilibrium, where $F'(\bar{E}+\Delta) = p$, we can write

$$\begin{aligned}\hat{p} &\cong p\,(1+p\bar{\gamma}) \cong p\,\left(1+\bar{\gamma}\,F'(\bar{E}) + \Delta\bar{\gamma}\,F''(\bar{E})\right) \\ &= p\,\left(1+\varepsilon(\bar{E}) + \frac{\Delta}{\bar{E}}\,\varepsilon(\bar{E})\,\frac{\bar{E}\,F''(\bar{E})}{F'(\bar{E})}\right) \cong p\,\left(1+\varepsilon(\bar{E})\right)\end{aligned} \tag{20}$$

using, in the last equation, that $\Delta/E << 1$, while ε and the emissions elasticity of marginal output are assumed to be of order of magnitude one.[5] This allows us to interpret τ as a small ad valorem tax determined by the emissions elasticity of output: τ≈ε. Furthermore,

ε can in turn also be viewed as proxy for the value share of emissions or–if emissions are seen as mainly energy related–energy's share. Such an interpretation would be in line with data showing energy's share to be on average around a few percent (Kümmel, Henn, and Lindenberger, 2002).

5. Conclusion

Based on an analytical approach, we investigated the effects of emissions trading between countries with different types of emission control mechanisms, namely absolute targets and intensity targets. This constitutes an important question, since international climate policy currently shows a tendency towards increased fragmentation, rendering the simultaneous presence of multiple approaches – and the need for their integration – quite possible.

By considering two countries that both produce output by means of a concave production function with emissions as the sole input, but that are subject to different types of emission targets, we derived three results: first, emissions trade across these two different policy regimes increases global emissions, but only if the country with intensity target is a net buyer of permits; otherwise global emissions decrease. Second, emissions trade always leads to equilibria not satisfying Pareto efficiency. Third, we propose a suitable tax on traded permits to be adopted by the country with the intensity target that restores Pareto efficiency. A rough empirical estimate suggests that an ad valorem tax of few percent would be optimal when considering the economy as a whole. However, this figure could be significantly higher if intensity targets are employed to cover highly carbon intensive segments of the economy within so-called sectoral approaches.

Endnotes

[1] See http://www.whitehouse.gov/news/releases/2002/02/climatechange.html

[2] Note that the derivative is given by

$$d\gamma/dE = \left(F(E) - E\,F'(E)\right)/F^2(E) = 1/F(E)\left[1-\varepsilon(E)\right] > 0\,.$$

[3] It is assumed that the tax revenue is recycled back as a lump sum.

[4] Data for 2004 taken from the World Resource Institute's CAIT database.

[5] If *F* is power law function with exponent a<1, the latter would be 1-a.

References

Aldy, J., Stavins R.N., (eds), 2007, *Architectures for Agreement: Addressing Global Climate Change in the Post-Kyoto World*, Cambridge University Press, Cambridge UK.

Biermann, F., Pattberg, P., Asselt, H. van, Zelli, F., 2007, *Fragmentation of Global Governance Architectures - The Case of Climate Policy*. Global Governance Working Paper 34. Available at http://www.glogov.org/images/doc/WP34.pdf

Bodansky, D., 2004, *International Climate Efforts Beyond 2012: A Survey of Approaches,* PEW Center report. Available for download at http://www.pewclimate.org/docUploads/2012%20new.pdf

Chang, C.-C., Mendelsohn, R.O., Shaw, D. (eds), 2003, *Global warming and the Asian Pacific,* Edward Elgar Publishing, Cheltenham.

Edenhofer O., Flachsland, C., and Marschinski, R.,2007, T*owards a Global* CO_2 *Market? Expertise for the Policy Planning Staff in the Federal Foreign Office*, Potsdam Institute for Climate Impact Research.

Fischer C., 2003, 'Combining rate-based and cap-and-trade emissions policies', *Climate Policy* 3, Supplement 2, 89-103.

Frankel, J.A., 1999, *Greenhouse Gas Emissions*, Brookings Institution Policy Brief 53, Brookings Institution, Washington DC.

Government of Canada, 2007, *Regulatory Framework for Air Emissions*. Available at http://www.ecoaction.gc.ca/news-nouvelles/pdf/20070426-1-eng.pdf

Harvard Project on International Climate Agreements Special Paper Competition. Information available at http://belfercenter.ksg.harvard.edu/publication/17879/harvard_project_on_international_climate_agreements_special_paper_competition.html

Herzog, T., Pershing, J., and Baumert, K., 2006, *Target: Intensity. An Analysis of Greenhouse Gas Intensity Targets*, World Resources Institute, Washington DC.

ICAP International Carbon Action Partnership, 2007, *Political Declaration*. Available for download at http://www.icapcarbonaction.com/docs/icap_declaration.pdf.

Kolstad, C.D, 2005, 'The simple analytics of greenhouse gas emission intensity reduction Targets', *Energy Policy* 33, 2231-2236.

Kümmel, R., Henn, J., Lindenberger, D., 2002, 'Capital, labor, energy and creativity: modeling innovation diffusion'*, Structural Change and Economic Dynamics* 13, 415-433.

Lisowski M., 2002, 'The emperor's new clothes: redressing the Kyoto Protocol', *Climate Policy* 2, 161-177.

Marschinski, R., Lecocq, F., 2006, *Do Intensity Targets Control Uncertainty Better than Quotas? Conditions, Calibrations, and Caveats*, World Bank Policy Research Working Paper 4033, Washington DC.

Nordhaus, W.D.,1992, 'An optimal transition path for controlling greenhouse gases'*, Science* 258, 1315-1319.

Nordhaus, W.D., Yang, Z., 1996, 'A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies'*, The American Economic Review* 86 **4**, 741-765.

Quirion, P., 2005, 'Does uncertainty justify intensity emission caps?', *Resource and Energy Economics* 27(4), 343-353.

Schmidt J., Helme, N., Lee, J., and Houdashelt, M., 2006, *Sector-based Approach to the Post-2012 Climate Change Policy Architecture*, FAD Working paper, Center for Clean Air Policy (CCAP), Washington DC.

Victor, D., 2007, 'Fragmented carbon markets and reluctant nations: implications for the design of effective architectures', in: Aldy, J.E., Stavins, R.N. (eds), *Architectures for Agreement. Addressing Global Climate Change in the Post-Kyoto World*, Cambridge University Press, Cambridge UK, 133-160.