Optimal Intensity Targets for Greenhouse Emissions Trading under Uncertainty

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Abstract:

Uncertainty is an obstacle for commitments under cap and trade schemes. We assess how well intensity targets, where countries' permit allocations are indexed to future realised GDP, can cope with uncertainties in international greenhouse emissions trading. We present some empirical foundations for intensity targets and derive a simple rule for the optimal degree of indexation to GDP. Using an 18-region simulation model of a cooperative, global cap-and-trade treaty in 2020 under multiple uncertainties and endogenous commitments, we show that optimal intensity targets could reduce the cost of uncertainty and achieve significant increases in global abatement. The optimal degree of indexation to GDP would vary greatly between countries, including super-indexation in some advanced countries, and partial indexation for most developing countries. Standard intensity targets (with one-to-one indexation) would also improve the overall outcome, but to a lesser degree and not in all individual cases. Although target indexation is no magic wand for a future global climate treaty, gains from reduced cost uncertainty and the potential for more stringent environmental commitments might justify the increased complexity and other potential downsides of intensity targets.

Keywords: Climate policy, emissions trading, uncertainty, flexible targets, intensity targets, optimality, simulation modelling.

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1. Introduction

Uncertainty can be a major impediment for cap-and-trade schemes for emission permits, be they greenhouse gases or other pollutants. Setting fixed emission caps or targets can give greater certainty about future emission levels and perhaps environmental impacts, but in so doing it creates uncertainties about costs of complying with the commitments. Economic uncertainty is often a rallying point for opposition against environmental policy, whether implemented by regulation or by market mechanisms. Where compliance costs are uncertain, environmental commitments tend to be watered down. Where those regulated have a strong degree of sovereignty, as in international negotiations, uncertainty can even preclude an agreement altogether.

International climate negotiations are a case in point. After the Kyoto Protocol was signed in 1997, debate raged over how much the Kyoto commitments would cost (Toman 2004). Estimates diverged widely (Weyant 1999), and the fact that meeting the Protocol's fixed quantity targets might have led to comparatively high costs, even under international emissions trading, contributed to the United States pulling out of the agreement. Bringing developing countries on board, essential for a meaningful post-Kyoto treaty, brings even greater challenges from economic uncertainty. Poor countries' decision-makers can ill afford to sign a treaty that risks major cost blow-outs or 'stifling development'. And although it is well established in theory that price control (i.e. a tax) is preferable to quantity control (i.e. cap-and-trade) under cost uncertainty and for pollutants with a flat marginal damage function, such as greenhouse gases (Weitzman 1974, Pizer 2002), cap-and-trade is fast becoming the dominant instrument for national and international greenhouse gas control. The European CO_2 Emissions Trading Scheme (ETS) is the largest commitment to this instrument so far, and a number of US States are considering their own cap-and-trade systems.

It is therefore of key relevance to climate policy to ask: can cap-and-trade schemes be better designed to reduce uncertainty? If so, environmental agreements can become both more achievable *and more effective*, by including targets which are more stringent overall, even if not at every place and time. Of several design features proposed to reduce uncertainty, perhaps the most widely discussed, and the one we study here, is making emission targets more flexible by indexing target allocations to GDP. They then become targets for the emissions/GDP ratio, that is, emissions *intensity targets* (also referred to as 'relative', 'rate-based', or 'dynamic' targets), designed to compensate for fluctuations in emissions caused by fluctuations in economic activity.

Target indexation has been proposed as a way for making it easier for developing countries to commit to greenhouse targets, and featured in Argentina's greenhouse target proposed in the aftermath of the Kyoto negotiations. The Bush administration, after rejecting the Kyoto Protocol in 2001, set a target for future carbon intensity of the US economy. Even though this target is close to business-as-usual and therefore has little meaning in practical terms, it sparked renewed interest in the concept of intensity targets, and also brought a greater political dimension to what is essentially a technical issue of mechanism design. However, intensity targets have been criticised for increasing uncertainty in year-by-year emission levels under a treaty, possibly weakening environmental commitments, and for bringing greater complexity.[2]

Here we use a single-period, stochastic, globally integrated, though mainly partial equilibrium, model of emissions trading with flexible targets under uncertainty, named MAGES (Mechanisms for Abating Global Emissions under Stochasticity), to extend the analysis of greenhouse intensity targets under uncertainty significantly beyond that in the literature so far. Crucially, this is a *multi*-country, empirical model, which automatically transmits uncertainty between countries via the global permit price; and it allows expected target levels to be *endogenous*, that is to fall (become more stringent) in response to the lower cost of uncertainty that intensity targets deliver for risk-averse countries.[3] This is in contrast to existing analytic contributions by Sue Wing et al. (2006), Quirion (2005) and Kolstad (2005), all of which considered single countries with fixed (exogenous) expected target levels. Our model also allows general intensity targets, defined by a continuous degree of indexation to GDP, and thus allows a distinction between *standard* intensity targets, with one-to-one indexation, and *optimal* intensity targets, where a partial degree of indexation is individually chosen to minimise a country's cost of uncertainty. Partial indexation has been considered by Sue Wing et al. (2006) and earlier in a foundation, less analytic paper (Ellerman and Sue Wing 2003), but here in a multi-country model it yields initially surprising recommendations for the degrees of indexation that different types of countries should use.

In Section 2 we discuss the empirical underpinnings of intensity targets, give our formal definition of general intensity targets under uncertainty, and derive our rule for optimal indexation. Section 3 describes the MAGES permit trading model under uncertainty and risk aversion, and its calibration as an 18-country (or region) model of a cooperative (non-free-riding) post-Kyoto treaty for all countries and most greenhouse

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[2] On proposals for intensity targets as a way to draw developing countries into a climate agreement, see Baumert et al. 1999, Frankel 1999, Lutter 2000, Philibert and Pershing 2001; on the Argentine target, see Bouille and Girardin 2002, Barros and Conte Grand 2002; on the Bush 'target', see for example van Vuuren et al. 2002, Blanchard and Perkaus 2004; and on criticism of target indexation, Dudek and Golub 2003, Müller and Müller-Fürstenberger 2003.

[3] A parallel paper, Pezzey and Jotzo (2006), investigates theoretical properties of the MAGES model under risk neutrality.

gas emissions in 2020. Simulation results and sensitivity analysis are presented in Section 4, for scenarios with absolute, standard intensity (one-to-one indexation) and optimal intensity targets. Section 5 discusses issues of framing, potential drawbacks and practical applicability of intensity targets, and here we especially address the criticism that intensity targets increase emissions uncertainty and thereby undermine environmental integrity. Section 6 concludes.

2. Formulation of intensity targets

After discussing the empirical background for intensity targets, here we analyse future business-as-usual (BAU) emissions as a function of three separate uncertainties.[4] This is complemented by a generalized formulation of emission targets indexed continuously to GDP. We then derive a simple rule for optimal indexation of targets, and show the conditions for a 'standard' intensity target with one-to-one indexation to reduce net emissions uncertainty compared to an absolute target.

2.1 Empirical background

The concept of intensity targets as a means to reduce uncertainty rests on the assumption that GDP and emissions move together. To this end, we are interested in the co-movement of fluctuations in emissions and fluctuations in GDP – what happens to emissions when the economy grows at below or above average rates.[5]

Several studies have examined the GDP-emissions relationship empirically in the context of intensity targets, using various methods including statistical forecasting models applied to historical data and analysis of past published emissions forecasts (Lutter 2000, Sue Wing et al. 2006, Philibert 2004), analysis of co-movement of series over time (Höhne and Harnisch 2002), and country case studies (Kim and Baumert 2002, Bouille and Girardin 2002). Each of these studies confirms that emissions tend to fluctuate to some degree with fluctuations in GDP, though the nature and degree of linkage estimated varies.

Our own empirical work (Jotzo 2006a) shows a significant positive correlation between deviations of GDP from trend and deviations of emissions from fossil fuel combustion from trend, for 23 out of the 30 largest emitting countries over the period 1971–2000. The strength of the correlation varies greatly between countries, with a mean and median around one. Thus in most countries, emissions on average move in tandem with GDP, but with large divergences from the mean in individual episodes due to changes in emissions intensity. No such correlation is evident between GDP and non-CO_2 greenhouse gas emissions, and between GDP and emissions from land-use change.

Intensity targets will be able to deal only with GDP-related uncertainty, not uncertainty about future emissions intensity, or uncertainty in parts of the economy

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[4] Throughout, we treat 'uncertainty' as the same, quantifiable concept as 'risk', rather than Knightian (unquantifiable) uncertainty.

[5] This question is quite distinct from the long-term structural relationship between economic growth and greenhouse emissions that is the subject of most of the ample literature on the relationship between GDP and emissions (such as Holtz-Eakin and Selden 1995, Schmalensee et al. 1998).

where emissions are independent of GDP. For the calibration of the simulation model described below, we need empirical estimates of the magnitude of these uncertainties. Results from statistical forecasting models applied to historical data (again see Jotzo 2006a) indicate that uncertainty about future GDP is sizeable, but significantly smaller than uncertainty about emissions intensity. Uncertainty is greater in non-OECD than in OECD countries; and uncertainty about non-energy sector emissions is of a similar broad magnitude as that for emissions intensity from fuel combustion. We will assume that realizations of random variables are independent of each other, and in particular that deviations of emissions intensities in the energy sector from their expectations are independent of GDP deviations. This independence assumption is supported by results from the statistical analysis. Table A1 in the Appendix gives our projections for 2020, including the estimated standard deviations, which are used as parameter values in the MAGES model.

2.2 Future emissions and uncertainties

We assume that emissions in one part of the economy are linked with GDP, though the link is not perfect because emissions intensity also fluctuates. Aggregate uncertainty about future business-as-usual (BAU) emissions in the model stems from three separate sources. They are:

- uncertain output, measured by GDP and denoted $\tilde{Y}_i$ \$/yr, where *i* denotes one of the many countries or regions into which the world is divided (18 of them in our empirical model), and \$ means constant 2000 US dollars);
- uncertain emissions intensity of output in the 'linked' part of the economy, denoted $\tilde{\eta}_i$ t/\$, where t means a tonne of CO_2-equivalent emissions; and
- uncertainty in other, not GDP-linked emissions.

Future BAU emissions in a particular random realization are thus equal to expected BAU emissions times adjustments for expectation errors for GDP, emissions intensity and emissions in the non-linked sector.

Formally, realized BAU emissions for country *i* are

$$\tilde{E}_i^b = E_i^b[1+\alpha_i(\varepsilon_{Yi}+\varepsilon_{\eta i})+(1-\alpha)\varepsilon_{\rho i}] \qquad [2.1]$$

where our notation is

$\tilde{E}_i^b$	Actual BAU emissions in a particular random realization (in t/yr)
E_i^b	Expected BAU emissions
α_i	Fixed share of the economy where emissions are linked with GDP ($0 \le \alpha_i \le 1$)

ε_{Yi}	Proportional deviation ('error') of actual GDP $\tilde{Y}_i$ from its expectation Y_i
$\varepsilon_{\eta i}$	Proportional deviation of actual emissions intensity $\tilde{\eta}_i$ in the 'linked' sector from its expectation η_i.
$\varepsilon_{\rho i}$	Proportional deviation of actual emissions from expectations in the 'non-linked' sector.

As introduced above and throughout this paper, a tilde (~) superscript denotes a particular realization of a random variable, whereas no superscript denotes its expectation of a random variable. And the disappearance of subscript i or k denotes summing over all countries: $\Sigma_i J_i = \Sigma_k J_k =: J$, for any variable or parameter J.

Error terms ε_{Yi} and $\varepsilon_{\eta i}$ are assumed to be additive rather than multiplicative, to keep the stochastic analysis tractable. We assume that the error terms are distributed normally and are independent of each other, with

$$\varepsilon_{Yi} \sim \mathrm{N}(0,\sigma_{Yi}),\ \ \varepsilon_{\eta i} \sim \mathrm{N}(0,\sigma_{\eta i}),\ \text{ and } \varepsilon_{\rho i} \sim \mathrm{N}(0,\sigma_{\rho i})\ . \qquad [2.2]^{6,7}$$

So GDP uncertainty ε_{Yi} affects emissions in the α_i proportion of the economy, but structural shifts and other random influences ($\varepsilon_{\eta i}$) also play a role here; while in the other, ($1-\alpha_i$) proportion, emissions are independent of GDP and subject to random shocks $\varepsilon_{\rho i}$.

The σ_i parameters are measures of the degree of uncertainty. Numerical calibration is done based on the empirical estimates described in Section 2.1 above (see also Appendix). Again following empirical findings, we assume that the share α_i of emissions linked with GDP in each region is equal to the share of the energy sector in total emissions. This assumption would obviously need to be refined for detailed country-level analyses, which ideally would rely on more disaggregated data.

Expected BAU emissions E_i^b, GDP Y_i and population L_i are calibrated on the basis of levels reported for the years 2002/2000, and forecasts by the main forecasting agencies. The Appendix gives sources and shows all parameter values used.

2.3 Emissions targets

Next, we define a general flexible target (or permit allocation), defined as a ratio of expected future BAU emissions and adjusted for realized GDP, as

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[6] In the numerical simulations, these error terms (as well as the error term ε_{Ci} introduced below) are truncated at two standard deviations above and below zero. This is done in order to exclude unrealistic realisations at the extreme tails of the probability distributions.

[7] In practice, these deviations from expectations will of course not always be uncorrelated. However, our empirical analysis (Jotzo 2006a) indicates that there is no systematic correlation between ε_{Yi}, $\varepsilon_{\eta i}$ and $\varepsilon_{\rho i}$.

$$\tilde{X}_i = x_i E_i^b (1 + \beta_i \varepsilon_{Yi}) \qquad [2.3]$$

with notation

$\tilde{X}_i$	realised target (in t/year)
x_i	target as a proportion (> 0, perhaps > 1) of expected future BAU emissions
β_i	degree of indexation of the target to GDP (≥ 0)

and E_i^b and ε_{Yi} are as defined above.

By how much the realised target gets adjusted for a deviation in GDP from its expected value depends on β_i, its degree of indexation. Two obvious special cases are

Absolute target, with no indexation ($\beta_i = 0$), hence $\tilde{X}_i = X_i = x_i E_i^b$; [2.4]

Standard intensity target, with one-to-one indexation ($\beta_i = 1$), hence $\tilde{X}_i = x_i E_i^b (1 + \varepsilon_{Yi})$. [2.5]

So in our terminology, Kyoto Protocol targets are absolute; and what the literature usually refers to as 'intensity targets' are standard intensity targets. Partial indexation is possible and is discussed below. Importantly, with no GDP uncertainty, absolute and intensity targets are the same because they use the same x_i.

2.4 Optimal intensity targets

Since the error term ε_{Yi} appears in both realised BAU emissions and intensity targets, target indexation changes the variability of the effort implied by the target (the difference between BAU emissions and the target):

$$\tilde{E}^b{}_i - \tilde{X}_i = E^b{}_i - X_i + \tilde{N}_{Ei}, \text{ hence } \tilde{E}^b - \tilde{X} = E^b - X + \tilde{N}_E \ , \qquad [2.6]$$

where from [2.1] and [2.3], a country's net emissions uncertainty (net of any neutralising effect of the index β_i) is

$$\tilde{N}_{Ei} := [(\alpha_i - \beta_i x_i)\varepsilon_{Yi} + \alpha_i \varepsilon_{\eta i} + (1 - \alpha_i)\varepsilon_{\rho i}]\, E^b{}_i \, . \qquad [2.7]$$

The expectation of squared net emissions uncertainty, from [2.7] and [2.2], is also important:

$$D_{Ei} := \mathrm{E}[\tilde{N}_{Ei}^2] = [(\alpha_i - \beta_i x_i)^2 \sigma_{Yi}^2 + \alpha_i^2 \sigma_{\eta i}^2 + (1 - \alpha_i)^2 \sigma_{\rho i}^2]\, E_i^{b\,2} \ . \qquad [2.8]$$

Under the modelling assumptions set out in the next Section, particularly the assumptions that all countries take the global permit price as given, the expected global net benefit of the treaty is maximised when squared net emissions uncertainty D_{Ei} is minimised for all countries.[8] This occurs when GDP-related uncertainty σ_{Yi} is fully neutralised as regards the

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[8] This is shown formally in Pezzey and Jotzo (2006). We thank a referee for pointing out that under different market assumptions or net benefit functions, net benefit might not be maximised by minimising all D_{Ei}'s.

effort required to meet the target, which is achieved by setting β_i such that all $\alpha_i - \beta_i x_i = 0$. This in turn leads to our *rule for optimal indexation* of intensity targets:

Optimal indexation of emissions targets to GDP means

$$\beta_i^* = \alpha_i / x_i \text{ for all } i. \qquad [2.9]$$

Thus, the optimal degree of indexation depends on α_i, the share of total emissions linked with GDP, divided by x_i, the relative stringency of the target commitment. Together with [2.3], this defines an

Optimal intensity target as $\widetilde{X}_i = x_i E_i^b [1 + (\alpha_i / x_i)\varepsilon_{Yi}]$. [2.10]

For some countries, the share of emissions linked with GDP α_i may be greater than the target expressed as a share of BAU emissions, x_i. That is, an optimal intensity target may be *super-indexed* to GDP ($\beta_i^* > 1$), a possibility which will be realised for several countries in our empirical analysis.

Our finding that not just the degree of GDP-emissions linkage, but also the stringency of the target matters for the optimal degree of indexation, is in contrast to most earlier analyses on intensity targets which looked only at the emissions-GDP correlation, though it tallies with recent work by other authors. In a rather different analytical framework, Sue Wing et al. (2006, p.12) found that to reduce variability in abatement burden in an economy with steady economic growth, "… stringent emission targets should be implemented using intensity limits, while lax targets should employ absolute limits."

2.5 Does GDP indexation reduce uncertainty?

From [2.8], target indexation reduces uncertainty D_{Ei} if

$$(\alpha_i - \beta_i x_i)^2 < \alpha_i^2 \qquad [2.11].$$

So from [2.9], optimal intensity targets are always expected to reduce uncertainty (unless $\alpha_i = 0$ when optimal intensity and absolute targets coincide).

The impact of standard intensity targets by contrast is ambiguous, because they undercompensate for GDP-related fluctuations in emissions in cases where $\beta_i^* > 1$, and overcompensate where $\beta_i^* < 1$. However, with $\beta_i = 1$, [2.11] holds whenever

$$(0 <) x_i < 2\alpha_i \ , \qquad [2.12]$$

so standard intensity targets are expected to reduce uncertainty unless α_i, the degree of GDP-emissions linkage, is very small compared to x_i, the stringency of the target.

3. The MAGES model for emissions trading under uncertainty

To simulate the performance of intensity targets, we use the MAGES (Mechanisms for Abating Global Emissions under Stochasticity) model, a new static, stochastic, mainly partial equilibrium model of global emissions trading under uncertainty, calibrated for a global, post-Kyoto climate treaty, covering all greenhouse gases and taking effect in a single future time period, chosen here as the year 2020. We have chosen to divide the world into 18 regions or countries, hereafter just 'countries'. 5 are high-income countries known together as 'the North', while 13 are low-income ones ('South'). Our choice both represents the main players in global climate policy as single countries (such as the USA, EU, China and India), and allows detailed analysis for selected developing countries like Argentina and South Korea. The empirical calibration reflects key features of individual countries, while not aiming at 'exact' numerical representation. For a list of the 18 countries and their empirical calibration in MAGES, see Table A1 in the Appendix.

3.1 Abatement costs and benefits, and permit trading

The abatement treaty grants a flexible permit allocation $\{\tilde{X}_i\}$, comprising an (X_i, β_i) pair for each country, defining their $\tilde{X}_i$ as in [2.3]. Perfect enforcement in the global permit market makes abated emissions equal the target only globally:

$$\tilde{E} = \tilde{X}, \text{ hence global abatement } \qquad \tilde{Q} = \tilde{E}^b - \tilde{X}. \qquad [3.1]$$

The market price of a permit is $\tilde{p}$, assumed to be taken as given by all countries, and a country's emissions trading revenue is then

$$\tilde{R}_i := \tilde{p}[\tilde{X}_i - \tilde{E}^b{}_i + \tilde{Q}_i(\tilde{p})], \text{ with global } \tilde{R} \equiv 0 \text{ automatically.} \qquad [3.2]$$

Country *i*'s *net benefit* from emissions trading compared to no abatement anywhere[9] is defined as

$$\tilde{A}_i \qquad := \tilde{B}_i - \tilde{C}_i \;\; \$/\text{yr, where} \qquad [3.3]^{10}$$

$$\tilde{B}_i(\tilde{Q}) \qquad := V_i\tilde{Q} - \tfrac{1}{2}W_i(\tilde{Q})^2 + \tilde{R}_i, \;\; V_i \;\; \$/\text{t} > 0, \;\; W_i \;\; \$.\text{yr/t}^2 > 0, \qquad [3.4]$$

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[9] By comparing emissions trading with no abatement anywhere, rather than with no abatement by *i* while all other countries abate according to the treaty, we are setting aside the problem of free riding; see also 3.3 below.

[10] In a second-best world, this simple net benefit formula should be amended to allow for the marginal cost of public funds being greater than unity (Quirion 2004). Like several other features such as information and enforcement costs, this remains for further work, but it will in any case have little effect on the relative performance of absolute, standard intensity and optimal intensity targets as reported here.

is *i*'s dollar-valued (gross) benefit $\tilde{B}_i$ of global abatement $\tilde{Q}$, including its emissions trading revenue. We include valuation of (or benefits from) global abatement in order to be able to determine the optimal level of abatement, in the broad vein of Nordhaus (1991). Abatement benefits allow us to model how the reduced uncertainty cost from using a potentially better *type* of target mechanism (such as intensity targets) would be spent endogenously on achieving lower target *levels*, which in turn means greater welfare. This "endogenous targets" effect is a key contribution here, and we discuss it, and the calibration of the benefit parameters $\{V_i\}$ and $\{W_i\}$, further in Sections 3.3 and 3.4 respectively.

The cost of *i*'s own abatement $\tilde{Q}_i$ is

$$\begin{aligned}\tilde{C}_i(\tilde{Q}_i) &:= \tfrac{1}{2}\tilde{Q}_i^2/M_i + \tilde{Q}_i\varepsilon_{Ci} \\ &= \tfrac{1}{2}\tilde{Q}_i^2/M_i + \tilde{Q}_i\tilde{N}_{Ci}/M_i, \text{ with } \tilde{N}_{Ci} := M_i\varepsilon_{Ci}\,. \qquad [3.5]\end{aligned}$$

The marginal abatement cost (MAC) curve is then linear in $\tilde{Q}_i$, and uncertain:

$$\tilde{C}'_i(\tilde{Q}_i) = \tilde{Q}_i/M_i + \varepsilon_{Ci}, \qquad [3.6]$$

Here ε_{Ci} is Weitzman's (1974) 'pure unbiased [stochastic] shift' in the MAC. We assume $E[\varepsilon_{Ci}] = 0$, $E[\varepsilon_{Ci}^2] =: \sigma_{Ci}^2$, and ε_{Ci} is independent of all other uncertainties.[11] Hence from [3.3], [3.4] and [3.5], realised net benefit is

$$\tilde{A}_i = V_i\tilde{Q} - \tfrac{1}{2}W_i(\tilde{Q})^2 - \tfrac{1}{2}\tilde{Q}_i^2/M_i - \tilde{Q}_i\tilde{N}_{Ci}/M_i + \tilde{R}_{i.} \qquad [3.7]$$

A similar formula applies to the Unilateral case, denoted by the superscript ^{U}. Under unilateralism, each country decides on its own abatement effort $\tilde{Q}^U{}_i$ in isolation (i.e. assuming $\partial\tilde{Q}^U/\partial\tilde{Q}^U{}_i = 1$) and there is no trading revenue:

$$\tilde{A}^U{}_i := V_i\tilde{Q}^U - \tfrac{1}{2}W_i(\tilde{Q}^U)^2 - \tfrac{1}{2}(\tilde{Q}^U{}_i)^2/M_i - \tilde{Q}^U{}_i\tilde{N}_{Ci}/M_i. \qquad [3.8]$$

We do not model uncertainties in the benefits from global abatement, as under our independence assumptions, they would not affect the comparison of expected net benefit across mechanisms (though could perhaps have a minor effect on expected payoff, defined below). Stavins (1996), using a neglected result in Weitzman, noted that this convenient result does not hold if benefit and cost uncertainties are correlated. However, there is no evidence for such correlation in the greenhouse case, or reason to suspect its existence.

The abatement potentials $\{M_i\}$ in [3.5] are calibrated with reference to other studies, and the degree of uncertainty about abatement costs $\{\sigma_{Ci}\}$ can be gleaned by comparing MAC estimates from different models, indicating substantial uncertainty about abatement

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[11] In practice, deviations in abatement costs from their expectations may well be correlated to a degree with deviations from expected emissions intensity. Nevertheless, a large share of MAC uncertainty would stem from not knowing in advance the aggregate responsiveness of greenhouse gas emitters to price signals, independent of future emissions levels and intensity.

opportunities and costs (see Appendix). Calibration of the benefit parameters $\{V_i\}$ and $\{W_i\}$ in [3.4] is discussed in Section 3.4 below.

To maximise its financial benefit from emissions trading, each country chooses abatement $\tilde{Q}_i$ to equate its MAC $\tilde{C}_i'$ in [3.6] to the permit price $\tilde{p}$, which gives

$$\tilde{Q}_i = \tilde{p}M_i - \tilde{N}_{Ci}, \text{ and hence from [3.1] and [2.6]} \qquad [3.9]$$

$$\tilde{p} = (E^b - X + \tilde{N}_E + \tilde{N}_C)/M, \text{ with expectation} \qquad [3.10]$$

$$p = (E^b - X)/M. \qquad [3.11]$$

[3.10] clarifies an important reason for choosing a multi-country model. It is not just each country's own uncertainty that affects its position under emissions trading, but uncertainty in all other participating countries as well, transmitted through the realised permit price $\tilde{p}$. How much this deviates from its expectation p depends on deviations from expectations $\tilde{N}_E$ in BAU emissions and $\tilde{N}_C$ in MACs in all countries. So a flexible target that neutralises some uncertainty in one country has flow-through effects for all others in the permit market.

3.2 Payoff and risk aversion

We assume that country *i* assesses the desirability of a move from unilateral to treaty abatement by calculating its *expected payoff* from the move, which is best viewed as comprising three steps.

First, *i*'s *realised gain* from the move is defined from [3.7] and [3.8] as the difference in realised net benefits between the treaty and unilateral outcomes:

$$\tilde{G}_i := \tilde{A}_i - \tilde{A}^U{}_i\,. \qquad [3.12]$$

Then its *realised payoff* from the move is a risk-adjusted, strictly concave function of gain:

$$\tilde{U}_i := \tilde{G}_i + z_i(1 - e^{-r\tilde{G}_i}) \text{ \$/yr}; \quad z_i \text{ \$/yr} > 0\,, \quad r \text{ yr/\$} > 0. \qquad [3.13]$$

This captures *i*'s aversion to risk, by weighting potential losses more heavily than potential gains, in line with what we perceive to be the political psychology of international treaties. Risk aversion is a prerequisite for modeling endogenous targets. Without risk aversion, the overall target X is almost completely independent of the type of mechanism, and almost the only advantage of intensity targets is in reaching a given target at lower expected cost.[12]

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[12] With absolute and optimal intensity targets, the $(\alpha_i - \beta_i x_i)$ terms in [2.8] all become α_i or 0; and this means that without risk aversion (where $r = 0$ so $U = G$), our maximising criterion [3.15] below results in the same expected global target, X. With standard intensity targets, the $(\alpha_i - \beta_i x_i)$ terms are all $\alpha_i - x_i$; but for our calibration at least, this means that maximising G gives an X only very slightly (well under 1%) different from the X found for absolute and optimal intensity targets.

Finally, country *i*'s expected *payoff* is then, since all the errors have normal distributions with zero means,

$$U_i := \int_{\mathrm{R}^{4n}} [\widetilde{G}_i(\varepsilon) + z_i(1\text{-}e^{-r\widetilde{G}_i(\varepsilon)})]\ [e^{-\frac{1}{2}\Sigma[(\varepsilon_{Yi}/\sigma_{Yi})^2+(\varepsilon_{\eta i}/\sigma_{\eta i})^2+(\varepsilon_{\rho i}/\sigma_{\rho i})^2+(\varepsilon_{Ci}/\sigma_{Ci})^2]}$$

$$/\ (2\pi)^{2n}\Pi\ (\sigma_{Yi}\sigma_{\eta i}\sigma_{\rho i}\sigma_{Ci})]\ d\varepsilon,\ \text{ with}$$

$$\varepsilon := (\varepsilon_{Yi},\ldots\varepsilon_{Yn},\ \varepsilon_{\eta i},\ldots\varepsilon_{\eta n},\ \varepsilon_{\rho i},\ldots\varepsilon_{\rho n},\ \varepsilon_{Ci},\ldots\varepsilon_{Cn}). \qquad [3.14]$$

This will be less than expected gain G_i, by virtue of the positive parameters z_i and r. Importantly, the characterisation in [3.12]-[3.14] assumes that the payoff a country perceives is framed solely in terms of the financial and environmental consequences of the treaty, not the economy overall. We discuss this framing effect further in Section 5.1.

Expectation results, including expected payoff, are computed numerically by Monte Carlo simulations in a multi-stage algorithm. The model is solved for a large number of random realizations (here 10,000), with joint draws for each of the 18 x 4 = 72 stochastic parameters, and expectations computed as means over these realisations. In each simulation run, this is done for a given target vector $\{x_i\}$. In iterative re-runs of the simulation, the distribution of targets $\{x_i\}$ between countries is then adjusted to fulfill an equity constraint which we will discuss next; and finally the overall target X is adjusted to find the level of stringency at which global expected payoff is maximized, again finding $\{x_i\}$ that fulfills the equity constraint. In simulations with optimal intensity targets, we jointly optimise targets $\{x_i\}$ and indexation $\{\beta_i\}$.

3.3 Optimality, the equity criterion, and endogenous targets

For the case of a global climate treaty analysed here, the MAGES model is solved numerically as a *cooperative game*, by selecting both the overall size X and distribution $\{x_i\}$ of expected targets, so that

- expected global payoff U is *maximised* as just noted, subject to: [3.15]
- an *equity criterion* that all countries have the same expected payoff per person from the Treaty: $U_i/L_i = U_k/L_k$ for all i, k, where L_i, L_k are countries' populations. [3.16]

The equity constraint [3.16] is met solely through adjusting targets $\{x_i\}$, which we feel is politically more realistic than cash transfers, as assumed for example by Bohm and Carlén (2002). Some constraint like [3.16] is needed to achieve a plausible differentiation of targets $\{x_i\}$ between countries under global payoff maximization with endogenous targets. With unconstrained maximisation, countries that are least affected by uncertainty and risk aversion would be allocated extremely tight targets (low x_i's), while highly risk-averse countries would get implausibly generous targets. The equity criterion [3.16] is necessarily arbitrary (just as any exogenously imposed scheme of target differentiation would be), but in sensitivity analysis in Section 4.5, the choice of equity criterion makes little difference to the relative merits of absolute and intensity targets. What we will call the *Reference Case*, to which results for all other scenarios will be compared, is the outcome of applying [3.15] and [3.16] to emissions trading with *absolute targets*, and results for this are given in Section 4.1 below.

As foreshadowed above, a target type that neutralises some of the uncertainty will give greater payoffs, and because criterion [3.16] does not specify a direct rule for target distribution, in turn this leads to tighter targets (a lower X), i.e. *endogenous targets*. We thus model how better mechanism design improves environmental outcomes from a treaty. Of the many proposed rules for, and subsequent analyses of, target differentiation or `burden sharing' in greenhouse gas control (see for example Rose et al. 1998 or Berk and den Elzen 2001), most give *exogenous* targets.

As a participation constraint, we demand only that each country's payoff under the treaty is greater than if there was no treaty at all ($U_i > 0$). This quite weak constraint implicitly assumes that political cooperation can prevent free-riding (Eckersley 2004). The MAGES model could be extended to non-cooperative situations and thus analyse free-riding incentives, but this is left for further work.

3.4 Calibration of benefit and risk aversion parameters

As already noted, endogenous target levels are a key policy feature of our model, and emerge from choosing targets to maximise the net benefits of a policy mechanism, rather than just choosing a mechanism to minimise the cost of achieving exogenously fixed levels. But how should we calibrate the benefit valuation parameters $\{V_i\}$ and $\{W_i\}$? We chose not to use damage estimates as a proxy for each country's valuation of global abatement for three reasons: (a) damage estimates at the national level are highly speculative; (b) small differences in social discount rates translate to large differences in valuation because of the long time frames involved; and (c) high expected long-term damages from climate change in poorer countries do not necessarily translate to a correspondingly high willingness to pay for emission reductions now.

Instead, we calibrated the valuation parameters $\{V_i\}$ to conform with broad observations about the international debate about burden sharing, and this calibration is illustrative in nature. *Relative* per capita valuations $\{V_i/L_i\}$ are assumed to be a function of per capita income and historical responsibility for greenhouse emissions (cumulative emissions of energy CO_2 from 1970 to 2000 per capita), with per capita income weighted twice as heavily. This yields much higher $\{V_i/L_i\}$ in rich countries, but roughly an even split in total valuation V between North and South. W_i, the slope of the marginal benefit of GHG abatement curve, is chosen to be a small and constant share of V_i, resulting in a slight upward slope of the marginal benefit curve, in line with the well-recognised notion that since most greenhouse gases are long-lived stock pollutants, the marginal damage curve is almost flat (Pizer 2002).

In calibrating the risk aversion parameters $\{z_i\}$ and r in [3.13], we first choose all $z_i = 1/y_i$, with $y_i = Y_i/L_i$, per capita GDP. The $1/y_i$ factor matches the stylised fact that uncertainty matters more in poor countries, and thus captures an essential feature of the global climate policy debate. The payoff concavity parameter r is then calibrated so that risk aversion results in significantly less stringent commitments under uncertainty, but without stifling agreement altogether. In the default calibration, r is chosen so that global abatement in the Reference Case is *one quarter* lower than it would be without risk aversion. Overall global valuation parameters V and W, in conjunction with r, are chosen so that our Reference Case of a global climate treaty results in approximately a halving of global emissions growth between 2002 and 2020, compared to BAU.

4. Performance of intensity targets

How large are the potential improvements from intensity targets, and how important is optimal indexation? What are the key factors influencing the performance of intensity targets? This section explores these questions empirically through simulations using our model. We briefly describe the Reference Case, discuss aggregate and country-level results for the comparative performance of intensity targets, and then present alternative scenarios and sensitivity analysis.

4.1 Reference Case

The Reference Case assumes that all countries participate in a cap-and-trade treaty with absolute targets (no indexation, all $\beta_i = 0$), covering all major greenhouse gases. The Reference Case is a point of comparison for alternative scenarios with different types of intensity targets, not a prediction of a future climate treaty. Table I shows a summary of reference case results for the North/South country groups. Country targets $\{x_i\}$ are shown in Table III below.

(TABLE 1 ABOUT HERE)

Global abated emissions in the Reference Case, equal to the total amount of permits (E=X), grow by 15% from 2002 to 2020, compared to a projected 30% under BAU (E^b). This is equivalent to a reduction of 12% below global BAU emissions ($x = 0.88$), as shown in Table I. The Reference Case thus describes a significant but arguably realistic level of effort. The expected amount of abatement undertaken under the treaty is 6.5 Gt/yr, which compares to expected abatement in the unilateral case of 0.9 Gt/yr, calculated using [3.8].[13] The expected permit price p from [3.11], equal to expected the marginal cost of abatement in all countries, is 15 \$/t (of CO_2-equivalent), well within the range of estimates of the marginal damage of greenhouse gas emissions in the literature (Tol 2005), and comparable to prices paid in 2005 for permits under the EU CO_2 emissions trading scheme. Global dollar-valued global gain G from the climate treaty, defined as the expected sum of [3.12], is over 50 billion \$/yr, translating into a somewhat lower payoff U after adjustment for risk aversion (from [3.14]). The expected global cost of abatement, C from summing [3.5], is well below 0.1% of projected global GDP, which reassures us that this is an acceptable application of a partial equilibrium model.

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[13] The magnitude of abatement in the unilateral case, where each region maximises their own expected benefit without regard to decisions by others, depends on the degree of aggregation. In a regionally more aggregated model, unilateral abatement would be larger, because each region captures a greater share of external (global) benefits of its abatement action.

The emission targets $\{x_i\}$ used for the Reference Case are chosen to satisfy [3.15] and [3.16], that is to maximise expected global (risk-adjusted) payoff from a treaty subject to per capita payoff being equalised across all countries. Targets are strongly differentiated between countries, with stricter targets applying where relative valuation of abatement is higher, abatement is cheaper, and uncertainty or risk aversion lower. Table I shows that on the whole, high-income 'Northern' countries have relatively stringent targets and buy permits, while poorer countries abate their emissions below their targets and sell the freed-up permits, taking advantage of their relatively generous targets and relatively greater abatement options (for more detail, see left hand columns in Table III below). Compared to base year (2002) emissions, 'Southern' countries' targets are above their current emissions, leaving room for future emissions growth. The South as a group would receive substantial permit revenue, almost offsetting their overall abatement cost.

4.2 Exogenous intensity targets

We model two types of intensity targets:

- *standard intensity targets* with one-to-one indexation to GDP for all countries *i* (β_i = 1 as in [2.5]); and
- *optimal intensity targets*, where $\beta_i^* = \alpha_i/x_i$ for all *i* as in [2.10], so uncertainty due to fluctuations in GDP is fully neutralized.

In a first set of scenarios, we hold targets X_i exogenously fixed at Reference Case levels, but allow for target indexation by setting all $\beta_i = 1$ or α_i/x_i. This allows for an analysis of just the cost effectiveness of using indexation to achieve a given global abatement target under uncertainty.

Global results are reported in Table II. Expected abatement is unchanged by virtue of holding target levels fixed. The expected global gain G increases by 5% and 7% respectively under standard and optimal intensity targets. This estimated improvement in expected gain under fixed target levels does *not* depend on our assumptions about risk aversion and payoff, but derives directly from reduced cost uncertainty. Increases in (risk-adjusted) expected payoff U from target indexation are substantially larger than in gain G, as they also take account of 'psychological' effects of a reduced risk of incurring losses under emissions trading.

(TABLE II ABOUT HERE)

Fixed, standard intensity targets do not necessarily lead increases in expected welfare in all countries. In some regions overcompensation under one-to-one indexation would in fact increase effective uncertainty relative to the Reference Case, as discussed in Section 4.4 below.

4.3 Endogenous intensity targets

We now allow the set of countries' target levels, $\{x_i\}$, to be determined endogenously by maximizing global expected payoff subject to equal per capita distribution of expected payoffs. With intensity targets neutralising some or all of the GDP-related uncertainty, greater payoff can be achieved at a different set of maximising targets to those under absolute targets. Our results show the degree to which this reduced uncertainty can achieve both tougher environmental commitments, i.e. lower $X = \Sigma x_i E^b{}_i$ (hence higher expected total abatement, $Q = E^b – X$), and higher payoff U. With endogenous intensity targets, expected global abatement increases by around one quarter (Table II, last two columns). Under optimal indexation, slightly larger improvements are possible than with standard intensity targets, because because not just target levels $\{x_i\}$ but also indexation levels $\{\beta_i^*\}$ are simultaneously free to vary (using [2.9] when maximising U in [3.15]. By contrast, the one-to-one indexation of standard intensity targets will on average over- or under-compensate for fluctuations in GDP. These quantitative estimates should be seen in the context of maximum improvement achievable if there was no uncertainty, which is one third, deriving from our choice of risk aversion parameter r (again see Table II).

Both expected gain and payoff are significantly greater under endogenous intensity targets, compared to the corresponding scenarios with exogenous targets. This is because in addition to part of their uncertainty being neutralized, countries are free to choose their levels of abatement (and then generally choose higher levels, closer to what would happen with no uncertainty). These results would hold also if not all countries take on intensity targets. Reduced uncertainty in one part of the world is transmitted between countries through less variability in the permit price, and in our modelling context, through greater overall abatement and payoff sharing.

4.4 Targets and optimal indexation by country

The globally averaged emissions target is respectively 2.8 and 3.2 percentage points more stringent under standard and optimal intensity targets than under absolute targets (Table III). For individual countries, the changes in endogenous targets vary greatly, here ranging from less than one to around ten percentage points.[14] This is because the

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[14] The move to a more flexible target type can lead to slightly *less* stringent targets (higher x_i) in some countries/regions, contrary to more stringent commitments in aggregate. This is because reducing the cost

degree to which intensity targets can help address uncertainty varies across countries. Neutralising activity-related emissions uncertainty brings the greatest advantage where the share of emissions linked with GDP (α_i) is large, where uncertainty about future GDP (σ_{Yi}) is large relative to other uncertainties, and where risk aversion (proxied by $1/y_i$) is strong. In addition, larger countries tend to be affected more strongly by emissions uncertainty (and benefit from reducing uncertainty), as their domestic circumstances affect the global permit price.

(TABLE III ABOUT HERE)

For Southern (mainly developing) countries as a group, the impact of indexation on optimal target levels is greater than for Northern countries. In particular, moving from standard to optimal intensity targets brings little change for North's targets overall, but rather more stringent targets in many Southern countries. So customising the degree of indexation plays a more important role in developing than in industrialized countries. This is because of systematic differences in the degree of emissions-GDP linkage α_i and relative targets x_i between countries, which enter the optimality condition $\beta_i^* = \alpha_i / x_i$ in [2.9]. In many industrialised countries α_i takes on comparatively large values, because of the dominance of emissions from fossil fuel combustion (Australia and Canada/New Zealand being notable exceptions). At the same time, richer countries get allocated comparatively stringent targets, so x_i are low. Together, this gives β_i^* in the broad vicinity of one for many 'Northern' countries, so standard intensity targets with one-to-one indexation would already do quite well.

For several countries, the constrained-optimal target is lower than the share of emissions linked with GDP, so super-indexation of targets is optimal ($x_i < \alpha_i$ means $\beta_i^* > 1$). Under a reasonably ambitious treaty, this is likely to happen in many advanced economies, with Japan's super-indexation of 1.3 being highest in our scenario.

In most developing countries by contrast, partial indexation would be optimal. Countries with large non-energy sector emissions would generally be best off with very low degrees of indexation. This is evident for Indonesia and Brazil, where a large share of emissions stems from deforestation, the rate of which is unlikely to move with overall GDP. Here, optimal indexation would be very low, for a treaty that includes all greenhouse gas sources. Determining the optimal degree of indexation for each country in practice would require empirical assessments of emissions-GDP linkage at the sub-sectoral level, and the sectoral coverage of an emissions target would be an important determinant of optimal indexation.

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of uncertainty has disproportionately large effects in some countries, and these gains are distributed across all countries under our equity rule [3.16], by way of adjusting target commitments.

In some countries, $x_i > 2\alpha_i$, so from [2.12] overcompensation under standard intensity targets would actually *increase* emissions uncertainty. If continuously differentiated indexation were not an option and each country only had the dichotomous choice between an absolute or a standard intensity target ($\beta_i = 0$ or 1), then global payoff would be maximized if some developing countries had absolute, and the rest had standard intensity targets. In our scenario, absolute targets are preferable for Brazil, Indonesia, the Rest of the World region (all of which have large emissions from land-use change) as well as – only just – Argentina and the South-East Asia region.[15] Optimally indexed targets would of course be preferable in all countries.

4.5 Sensitivity analysis

Here we test the sensitivity of results to changes in some key parameters and assumptions from the baseline values used so far (as described in Section 3.4 and the Appendix), for the scenarios with endogenous intensity targets. Results are given in Table IV, with comments as follows.

(TABLE IV ABOUT HERE)

Equity criteria

As foreshadowed earlier, our choice of equal per capita payoff as our standard equity criterion in [3.16] affects target levels and differentiation between countries, but makes little difference to the relative assessment of different types. For example, if the average global emissions reduction were applied uniformly to all countries (ie. $x_i = 0.88$ for all countries in the Reference Case, and likewise uniform percentage reductions under endogenous intensity targets), this would leave Southern countries with a much greater, and Northern countries with a much lesser, burden than in our Reference Case. Yet the increases in expected gain, payoff and global abatement from intensity targets differ only moderately from our baseline results.

Uncertainty about GDP

In further sensitivity analysis, the uncertainty parameter σ_{Yi} is reduced and increased by one third, compared to the baseline calibration. Predictably, the less reliable projections of future GDP are, the greater is the potential role for intensity targets. Also, the gap between standard and optimal indexation increases in σ_{Yi}. Greater uncertainty

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[15] By contrast, Sue Wing et al. (2006) found intensity targets preferable to absolute targets for all six developing countries they looked at. This is probably because they considered data for CO_2 from fossil fuel combustion only, whereas we include all major greenhouse gas emissions and sources.

about future GDP thus not only makes intensity targets more attractive, but also makes optimal indexation relatively more attractive, an outcome also found by Sue Wing et al. (2006) for the single-region case.

Risk aversion

If risk aversion is stronger than in our baseline calibration, the advantage of intensity targets is also greater; while if parties are less averse to the risk of losses, then designing mechanisms to mitigate risk is less important also. The greater the degree of risk aversion, the greater the increase in expected global abatement under endogenous targets – ranging from no or almost no change under risk neutrality, to much larger improvements than in our baseline results. Expected gain G and payoff U however are greater with intensity targets even under risk neutrality, as they are a function of net uncertainty at any given level of abatement.

GDP–emissions linkage

We first assume that only half (instead of all, as in the baseline) of energy sector emissions are linked with GDP, resulting in lower values for α_i across the board. Standard intensity targets on the whole then perform slightly *worse* than absolute targets, because they strongly overcompensate for fluctuations in GDP. Optimal intensity targets, at low levels of indexation, still improve the outcome compared to absolute targets. If instead the overall emissions-GDP linkage is stronger than in the baseline, both standard and optimal intensity targets bring greater improvements over absolute targets.

5. Drawbacks of target indexation

Here we discuss the key downsides of intensity targets, and address arguments made against indexation in some of the relevant policy literature.

5.1 Pro-cyclical effects and framing of uncertainty

In the model we have assumed that the (risk-adjusted) payoff a country perceives from joining an emissions trading treaty is framed as a function of just the financial and environmental consequences of joining the treaty, not of any broader economic stabilisation. This would seem logical from the point of view of the treaty negotiators and industries that will be subject to emissions control, but from the point of the view of the country, should not the broader effect of overall economic uncertainty on welfare be taken into account?

Which frame of reference to use for negotiation is a matter for political and psychological choice. Given the existence of emissions trading, an absolute emissions target is not an absolute constraint on GDP growth, but a financial stabiliser. Intensity targets by contrast are pro-cyclical. However, our reading of the debate is that governments and negotiators are much more concerned about uncertainty within a treaty and their obligations under it. Potential impacts on domestic industries' competitiveness have played a strong role in the Kyoto Protocol negotiations, but arguments of overall economic stabilization were rarely heard. The value of permits would be small relative to the size of economies (in our calibration around 0.8% of global GDP), so changes in permit allocations would only amount to very small fractions of the changes in GDP that trigger them.

5.2 Shifting uncertainty to emission levels

Under intensity targets, the overall amount of emissions allowable under a treaty with intensity targets is not fixed, so uncertainty to some degree is shifted away from costs and on to emissions levels (Dudek and Golub 2003). We find that this is not an effective argument against target indexation in the greenhouse case, for several reasons.

Firstly, we have shown that intensity targets can achieve both more stringent environmental commitments in expectation terms, and higher welfare. So higher *variability* in $\widetilde{X}$, the amount of *realised* emissions allowed under the treaty, is outweighed in welfare terms by a lower *level* of X, the *expected* emissions. Under our simulation scenarios, there is a greater than 80% chance that global emissions $\widetilde{X}$ under the treaty with optimal intensity targets are lower than under absolute targets, and actual abatement undertaken ($\widetilde{Q} = \widetilde{E}^b - \widetilde{X}$) is also greater in the majority of random realisations. And while intensity targets raise variability in total emissions, they actually lower variability in the amount of abatement.

Secondly, uncertainty about overall emissions is created only insofar as fluctuations do not cancel out between countries, that is under a global economic boom or slowdown. A more typical pattern is for some countries to grow slower than expected while others grow faster, with offsetting effects.

Finally, variability in emissions as a result of indexation of medium-term targets has a negligible effect on the existing, long-lived stock of greenhouse gases in the atmosphere. For example, the global atmospheric concentration of carbon dioxide is currently growing by about 2% per year, and fluctuations in emissions because of target indexation will amount to only a small share of this 2%. So any temporary over- or undershooting of desired emissions at some point in time can be compensated for by periodically re-negotiating expected target levels.

5.3 Complexity and window-dressing

By bringing into play GDP as an additional variable for permit allocation, intensity targets make monitoring, verification and administration of the trading scheme more complicated, and there may be complications with using GDP measures as an activity index, especially with regard to inflation-proofing (Müller and Müller-Fürstenberger 2003). Intensity targets would thus add extra administrative complexity to challenges such as distributional impacts and the risk of Dutch disease from selling permits, that any kind of emissions trading already poses for developing countries. Further, differentiating the degree of indexation would pose extra challenges for negotiations.

There is also a danger that the very framing of targets in terms of intensity could be used to undermine the environmental stringency of commitments at a political level, in a highly charged and often poorly informed public debate. A reduction in future greenhouse intensity 'looks' more stringent than its equivalent expressed as a change in absolute emissions, because emissions intensity in most countries declines anyway, and this can be used for political window-dressing. For example, the Bush administration announced a goal of an 18% decline in US greenhouse emissions intensity from 2002 to 2012. This is close to the expected business-as-usual path, and implies a substantial increase in emission levels, despite it being framed as a 'reduction' (in intensity). Window-dressing could be dealt with by presenting intensity targets in terms of their expected absolute emission levels with an adjustment term, as in [2.3].

6. Conclusions

Uncertainty about future paths of economic and emissions growth can be an important obstacle to effective emissions trading schemes, because of ex ante uncertainty about the cost of complying with emissions targets. Intensity targets, where permit allocations are linked to future uncertain GDP, have been proposed as a means to reduce cost uncertainty by compensating for activity-related fluctuations in emissions. We have provided a theoretical analysis of emissions trading with endogenous intensity targets under GDP-linked and other uncertainties in emissions, applied it in a new multi-country, single-period, mainly partial equilibrium, empirical model of emissions trading and endogenous targets under uncertainty with risk aversion, and discussed the findings in a policy context.

We have shown how, under which conditions, and by how much intensity targets could improve both participating countries' welfare and the environmental stringency of a 2020 cooperative climate treaty that covers all countries and the majority of greenhouse gases. *Standard* intensity targets, which are indexed one-to-one to GDP, can reduce overall cost uncertainty and lead to better outcomes than Kyoto-Protocol-style absolute targets, but they can systematically over- or undercompensate for GDP-related fluctuations. *Optimal* intensity targets, where the degree of indexation is the ratio of the extent of each country's GDP-emissions linkage to its proportional target commitment, always perform better than absolute targets. In the scenarios simulated here, optimal intensity targets would result in increases in global abatement of more than a quarter, compared to absolute targets, with improvements in expected welfare to match.

Optimal degrees of indexation would differ strongly between countries, with ‘super-indexation’ optimal for many rich countries. For example, we find that Japan’s and Europe’s emissions targets would optimally rise or fall by about 1.3% and 1.1% respectively, if their GDPs turn out 1% higher or lower than expected. For developing countries by contrast, optimal indexation would typically be only partial, making it all the more important to tailor indexation to countries’ circumstances. In five out of our 18 regions, an absolute target would even be preferable to one-to-one indexation, if a discrete choice had to be made; though optimal intensity targets always dominate.

Potential improvements from indexation depend on how uncertain future GDP is, how strong future links between fluctuations in emissions and in GDP are, and how risk-averse decision-makers are in negotiating a treaty. Intensity targets have downsides, including their pro-cyclical effects in terms of the economy as a whole, their greater complexity and lesser transparency, and a small uncertainty about the level of emissions under the treaty. None of these potential drawbacks are likely to deal intensity targets a fatal blow however, and they need to be assessed against the important opportunity highlighted here, that greater flexibility could both strengthen environmental commitments *and* raise welfare. A more complex, dynamical general equilibrium analysis of intensity targets seems unlikely to change this key conclusion.

In the context of ongoing UN climate negotiations, intensity targets may be particularly interesting for middle-income, industrializing countries that consider joining a successor treaty to the Kyoto Protocol. Further down the track they might be attractive for developing countries, and could even help make national-level emissions targets politically more palatable in the United States. Target indexation is unlikely to be sufficient by itself, though, to overcome deep-seated problems of cooperation, equity and politics that lie at the heart of the deadlock in global climate negotiations. Economic restructuring to achieve deep cuts in global greenhouse emissions will be costly, and rich countries will have to pay if it is to happen. Yet although flexible targets are no magic wand, in some cases they might just tip the political balance in favour of making environmental commitments.

Appendix: Calibration of the MAGES model

Emissions, GDP and population

Data for the base year 2000 are from the World Resource Institute's CAIT database version 3.0 (WRI 2005), which compiles data from a range of sources. In calibrating BAU emissions E^b_i we include carbon dioxide (CO_2) from the energy sector (combustion of fossil fuels, plus emissions from cement production), CO_2 from land-use change (mainly deforestation in tropical countries), and emissions of methane and nitrous oxide from a range of sources. Base data are for 2002 (CO_2) and 2000 (other greenhouse gases). Projected growth rates until 2020 for BAU CO_2 emissions from the energy sector are taken from projections by the US Energy Information Administration (EIA 2004) and International Energy Agency (IEA 2004). For non-energy GHG emissions, we use projections from US-EPA (2006). For land-use change we assume that annual emissions remain constant, in the absence of reliable projections. For GDP, we use purchasing power parity (PPP-) adjusted GDP in the year 2002 as the base data, and projections from EIA and IEA. Population growth is from United Nations (2004) projections. Base data again are from CAIT. All the resulting projections for 2020 are in Table A1.

(TABLE A1 ABOUT HERE)

Marginal abatement cost (MAC) curves

Abatement potentials M_i are calibrated for energy-derived CO_2 on the basis of structural characteristics of each country. The relationship between abatement potential, emissions intensity of electricity production, and the overall emissions intensity of the economy, is estimated using abatement cost estimates from computable general equilibrium models (Ellerman and Decaux 1998, Polidano et al. 2000). This yields a consistent set of abatement potentials for our calibration, which is more regionally disaggregated than published MAC estimates (see also Jotzo 2006b). For non-CO_2 emissions we derive relative abatement parameters from data cited by den Elzen and Lucas (2004); for land-use change, we assume that relative abatement potential is broadly in line with that for non-CO_2 emissions. MAC schedules in the model are linear. Linearisation does not greatly change estimates of total costs compared to empirically estimated MAC functions with a typical degree of convexity, for the levels of abatement considered in this application.

Uncertainties and the GDP-emissions link

The empirical basis for calibrating uncertainty parameters σ_{Yi}, $\sigma_{\eta i}$ and $\sigma_{\rho i}$ and the degree of GDP-emissions linkage α_i is described in Section 2.1, and further detail can be found in Jotzo (2006a). The abatement cost uncertainty parameter σ_{Ci} was estimated on the basis of the divergence between estimates for marginal abatement costs from ten models (Weyant 1999), and calibrated for p = 15 \$/t as in our Reference Case.

All uncertainty parameters σ are scaled back by one third compared to the original empirical estimates, in order to reduce any risk of overstating the degree of effective uncertainty in the MAGES model. The distribution of error terms ε is truncated at two standard deviations above and below zero, in order to exclude unrealistic realisations at the extreme tails of the probability distributions. Errors are thus truncated in just under 5% of individual realisations.

The parameter α_i (emissions linked with GDP) is set equal to the share of emissions from fossil fuel combustion and cement manufacturing in total emissions, projected for the year 2020.

Valuation of emissions reductions

See Section 3.4.

Tables

Table I Reference Case results

Expected values of:		Global	North	South
Target (permits) as share of BAU emissions	$X_i/E^b_i = x_i$	0.88	0.79	0.93
Permit price ($/t)	p	15.00		
Expected reduction commitment (Gt/yr)	$E^b_i - X_i$	6.46	3.89	2.57
Expected abatement (Gt/yr)	Q_i	6.46	1.39	5.07
Expected permit exports (Gt/yr)	$Q_i - (E^b_i - X_i)$	0	–2.50	2.50
Expected gain from treaty (net of costs) (G$/yr)	G_i	56.5	7.2	49.4
Expected (risk-adjusted) payoff from treaty (G$/yr)	U_i	47.6	6.8	40.8
Expected costs from abatement (G$/yr)	C_i	57.3	12.3	44.9

Table II Intensity targets: Global results

	Certainty equivalence (all $\sigma_i = 0$)	Absolute targets (Ref. Case, all $\beta_i = 0$)	Fixed exogenous targets (all x_i as in Reference Case)		Endogenous targets (all x_i optimised)	
			Standard intensity targets (all $\beta_i =1$)	Optimal intensity targets (all $\beta_i^* = \alpha_i/x_i$)	Standard intensity targets (all $\beta_i =1$)	Optimal intensity targets (all $\beta_i^* = \alpha_i/x_i^*$)
Expected values of:						
Abatement *Q* (Gt/yr)	8.6	6.5	6.5	6.5	8.0	8.2
Gain *G* (billion $/yr)	75.9	56.5	59.4	60.7	64.7	66.3
Payoff *U* (billion $/yr)	76.6	47.6	58.5	60.7	62.4	65.2
Percentage difference compared to absolute targets:						
Abatement *Q*	33%	-	0%	0%	24%	27%
Gain *G*	34%	-	5%	7%	14%	17%
Payoff *U*	61%	-	23%	27%	31%	37%

Table III Intensity targets by country

	Reference case		Endogenous intensity targets			Share of emissions linked with GDP
	Absolute targets ($\beta_i = 0$)		Standard intensity targets ($\beta_i = 1$)	Optimal intensity targets ($\beta_i^* = \alpha_i / x_i$)	Indexation under optimal targets	
Country/region (N = North)	Abated emis. relative to BAU emis. (E_i/E^b_i)	Target relative to BAU emis. (x_i)	Target relative to BAU emissions (x_i)		β_i^*	α_i
United States (N)	0.913	0.812	0.781	0.780	1.06	0.83
Europe (N)	0.933	0.748	0.727	0.727	1.13	0.82
Japan (N)	0.971	0.750	0.739	0.739	1.30	0.96
Australia (N)	0.874	0.810	0.796	0.795	0.81	0.65
Canada/NZ (N)	0.915	0.823	0.811	0.811	0.80	0.65
Russia	0.836	0.801	0.773	0.773	1.01	0.78
China	0.829	0.957	0.853	0.852	0.92	0.78
India	0.853	0.947	0.936	0.936	0.65	0.61
Brazil	0.876	0.904	0.897*	0.891	0.25	0.22
Argentina	0.890	0.853	0.843*	0.843	0.45	0.38
Mexico	0.884	0.832	0.819	0.819	0.79	0.65
Korea (S.)	0.923	0.815	0.801	0.800	1.16	0.93
Indonesia	0.859	0.928	0.922*	0.914	0.21	0.19
South-East Asia	0.876	0.899	0.891*	0.888	0.47	0.42
South Africa	0.861	0.810	0.796	0.795	1.12	0.89
Northern Africa	0.892	0.916	0.908	0.908	0.79	0.72
Middle East	0.875	0.914	0.895	0.895	0.79	0.71
Rest of world	0.882	1.014	1.026*	1.004	0.34	0.34
Aggregates:						
North	0.923	0.785	0.761	0.761	..	0.55
South	0.860	0.929	0.899	0.893	..	0.64
Global	0.881	0.881	0.853	0.849	..	0.82

*For these countries, the standard intensity target x_i exceeds $2\alpha_i$, and so *reduces* expected payoff compared to the Reference Case (see Section 4.4).

Table IV Sensitivity analysis

Scenario	Change to parameters (applies to all countries)	Change compared to absolute targets, under endogenous optimal intensity targets	
		Expected Abatement Q	Expected Gain G
Baseline	-	*27%*	*17%*
Uniform reduction commitments	Same x_i for all countries	21%	16%
Low GDP uncertainty	σ_{Yi} reduced by one third	12%	6%
High GDP uncertainty	σ_{Yi} increased by one third	41%	34%
No risk aversion	$r = 0$	0%	6%
High risk aversion	$r = 0.01$ (baseline $r = 0.085$)	37%	26%
Weaker GDP-emissions link	α_i halved	4%	2%
Stronger GDP-emissions link	$(1-\alpha_i)$ halved	36%	27%

Table A1: Baseline calibration of parameter values in the MAGES model

Country/region (N) = 'North'; the rest are 'South'	Population (projected at 2020)	GDP (PPP adj., projected at 2020)	Emissions (BAU)	Share of emissions linked with GDP (= energy sector share)	Absolute abatement potential	GDP uncertainty (standard deviation)	Emissions intensity uncertainty (standard deviation)	Emissions uncertainty outside energy sector (std.devn.)	MAC uncertainty (standard deviation, for $p = 15.33$)	Valuation (benefit) function: constant	Valuation (benefit) function: slope	Risk aversion: concavity of payoff function	Risk aversion: weight on risk averse part of payoff function
	billion	trillion US\$2000/yr	Gt/yr (in CO_2 equivalent)	..	G t^2/yr.\$	..	..	..	..	\$/t	yr/\$	yr/\$	\$/yr
	L_i	Y_i	E^b_i	α_i	M_i	σ_{Yi}	$\sigma_{\eta i}$	$\sigma_{\rho i}$	σ_{Ci}	V_i	W_i	r	$z_i=1/(Y_i/L_i)$
United States (N)	0.337	16.47	8.63	0.83	0.0504	0.13	0.15	0.20	4.2	4.54	0.045	0.085	0.020
[†]Europe (N)	0.568	17.99	6.23	0.82	0.0279					4.69	0.047		0.032
Japan (N)	0.127	4.71	1.52	0.96	0.0029					1.18	0.012		0.027
Australia (N)	0.024	0.87	0.66	0.65	0.0056					0.23	0.002		0.027
Canada / NZ (N)	0.041	1.56	1.06	0.65	0.0060					0.43	0.004		0.026
[†]Russia	0.186	2.88	3.15	0.78	0.0344	0.18	0.25			1.31	0.013		0.065
China	1.415	15.67	8.73	0.78	0.0993					3.52	0.035		0.090
India	1.332	6.67	3.00	0.61	0.0296					1.38	0.014		0.200
Brazil	0.215	2.37	2.64	0.22	0.0217					0.50	0.005		0.091
Argentina	0.044	0.73	0.49	0.38	0.0036					0.17	0.002		0.061
Mexico	0.123	1.74	0.93	0.65	0.0073					0.40	0.004		0.071
Korea (S.)	0.050	1.76	0.80	0.93	0.0041					0.39	0.004		0.028
Indonesia	0.254	1.39	3.47	0.19	0.0329					0.29	0.003		0.183
[†]South-East Asia	0.232	2.27	2.22	0.42	0.0183					0.48	0.005		0.102
South Africa	0.048	0.90	0.66	0.89	0.0062					0.25	0.002		0.053
[†]Northern Africa	0.190	1.19	0.75	0.72	0.0055					0.27	0.003		0.160
[†]Middle East	0.280	1.83	2.44	0.71	0.0204					0.49	0.005		0.153
[†]Rest of the World	2.254	5.32	6.96	0.34	0.0548					1.39	0.014		0.424
Aggregates:													
North	1.10	41.6	18.1	0.82	0.093	0.13	0.15	0.20	4.2	11.06	0.111	0.085	0.026
South	6.62	44.7	36.3	0.55	0.338	0.18	0.25	0.20		10.83	0.108		0.148
Global	7.72	86.3	54.4	0.64	0.431	..	..	0.20		21.89	0.219		0.089

[†] Europe includes Western and Eastern Europe (EU-28 countries plus Norway, Switzerland, Iceland and Balkan states; Russia includes Ukraine and Belarus; South-East Asia includes Brunei, Cambodia, Laos, Malaysia, Philippines, Singapore and Thailand (not Indonesia); Northern Africa includes Algeria, Egypt, Libya, Morocco and Tunisia; Middle East includes Afghanistan, Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates, Yemen; Rest of the World includes all other countries (including much of Africa, South America and South Asia).

References

Barros, V. and Conte Grand, M. (2002), "Implications of a Dynamic Target of Greenhouse Gases Emission Reduction: The Case of Argentina", *Environment and Development Economics* 7(3): 547-69.

Baumert, K. A., Bhandari, R. and Kete, N. (1999), *What might a developing country climate commitment look like?* World Resources Institute, Washington DC.

Berk, M. M. and den Elzen, M. G. J. (2001), "Options for differentiation of future commitments in climate policy: how to realise timely participation to meet stringent climate goals?" *Climate Policy* 1: 465-480.

Blanchard, O. and Perkaus, J. F. (2004), "Does the Bush Administration's climate policy mean climate protection?" *Energy Policy* 32(18): 1993-1998.

Bohm, P. and Carlén, B. (2002), "A cost-effective approach to attracting low-income countries to international emissions trading: theory and experiments", *Environmental and Resource Economics* 23: 187-211.

Bouille, D. and Girardin, O. (2002), "Learning from the Argentine voluntary commitment", in *Building on the Kyoto Protocol: Options for protecting the climate*, K. A. Baumert, O. Blanchard, S. Llosa and J. F. Perkaus (eds.), World Resources Institute.

den Elzen, M. G. J. and Lucas, P. (2004), "FAIR 2.0 – A decision-support tool to assess the environmental and economic consequences of future climate regimes", RIVM report 550015001/2003, RIVM, Bilthoven.

Dudek, D. and Golub, A. (2003), ""Intensity" targets: pathway or roadblock to preventing climate change while enhancing economic growth?" *Climate Policy* 3(Supplement 2): S21-S28.

Eckersley, R. (2004), "Soft Law, Hard Politics and the Climate Change Treaty", in *The Politics of International Law*, C. Reus-Smit (eds.), Cambridge University Press, Cambridge.

EIA (2004), "International Energy Outlook 2004", US Energy Information Administration, Washington DC.

Ellerman, A. D. and Decaux, A. (1998), "Analysis of Post-Kyoto CO2 emissions trading Using Marginal Abatement Curves", MIT Joint Program on the Science and Policy of Global Change, Report no. 40, Cambridge MA.

Ellerman, A. D. and Sue Wing, I. (2003), "Absolute versus intensity-based emission caps", *Climate Policy* 3(Supplement 2): S7-S20.

Frankel, J. A. (1999), "Growth Baselines: Reducing Emissions and Increasing Investment in Developing Countries", Brookings Policy Brief no. 52, Brookings Institution, Washington DC.

Höhne, N. and Harnisch, J. (2002), "Greenhouse gas intensity targets vs. absolute emissions targets", Paper presented at the Sixth International Conference on Greenhouse Gas Control Technologies, ECOFYS, Cologne.

Holtz-Eakin, D. and Selden, T. M. (1995), "Stoking the fires? CO2 emissions and economic growth", *Journal of Public Economics* 57(1): 85-101.

IEA (2004), *World Energy Outlook 2004*, OECD/International Energy Agency, Paris.

Jotzo, F. (2006a), "Quantifying uncertainties for emissions targets", Economics and Environment Network Working Paper EEN0603, Australian National University, Canberra, een.anu.edu.au.

Jotzo, F. (2006b), "Global climate policy after the Kyoto Protocol: Flexible economic mechanisms for South and North under uncertainty and institutional constraints", PhD thesis, Australian National University, Canberra.

Kim, Y.-G. and Baumert, K. A. (2002), "Reducing uncertainty through dual-intensity targets", in *Building on the Kyoto Protocol: Options for protecting the climate*, K. A. Baumert, O. Blanchard, S. Llosa and J. F. Perkaus (eds.), World Resources Institute.

Kolstad, C. D. (2005), "The simple analytics of greenhouse gas emission intensity reduction targets", *Energy Policy* 33(17): 2231-2236.

Lutter, R. (2000), "Developing Countries' Greenhouse Emissions: Uncertainty and Implications for Participation in the Kyoto Protocol", *Energy Journal* 21(4): 93-120.

Müller, B. and Müller-Fürstenberger, G. (2003), "Price-related sensitivities of greenhouse gas intensity targets", *Climate Policy* 3(Supplement 2): S59-S74.

Nordhaus, W.D. (1991), "To slow or not to slow: The economics of the greenhouse effect", *The Economic Journal*, 101(407): 920-37.

Pezzey, J. and Jotzo, F. (2006), "Mechanisms for abating global emissions under uncertainty", Economics and Environment Network Working Paper EEN0604, Australian National University, Canberra, een.anu.edu.au.

Philibert, C. (2004), "Flexible targets for developing countries", Paper presented at the 'International seminar on climate change', Seoul, October 2004.

Philibert, C. and Pershing, J. (2001), "Considering the options: Climate targets for all countries", *Climate Policy* 1(2): 211-227.

Pizer, W. A. (2002), "Combining price and quantity controls to mitigate global climate change", *Journal of Public Economics* 85: 409-434.

Polidano, C., Jotzo, F., Heyhoe, E., Jakeman, G., Woffenden, K. and Fisher, B. S. (2000), "The Kyoto Protocol and Developing Countries: Impacts and Implications for Mechanism Design", ABARE Research Report 2000.4, Australian Bureau of Agricultural and Resource Economics, Canberra.

Quirion, P. (2004), "Prices versus Quantities in a Second-Best Setting", *Environmental & Resource Economics* 29(3): 337-360.

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

Rose, A., Stevens, B., Edmonds, J. and Wise, M. (1998), "International Equity and Differentiation in Global Warming Policy: An Application to Tradeable Emission Permits", *Environmental and Resource Economics* 12(1): 25-51.

Schmalensee, R., Stoker, T. M. and Judson, R. A. (1998), "World Carbon Dioxide Emissions: 1950-2050", *Review of Economics and Statistics* 80(1): 15-27.

Stavins, R. N. (1996), "Correlated Uncertainty and Policy Instrument Choice", *Journal of Environmental Economics and Management* 30: 218-232.

Sue Wing, I., Ellerman, A. D. and Song, J. (2006), "Absolute vs. intensity limits for CO2 emissions control: Performance under uncertainty", MIT Global Change Joint Program Report no. 130, Massachusetts Institute of Technology, Cambridge, MA.

Tol, R. S. J. (2005), "The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties", *Energy Policy* 33(16): 2064-2074.

Toman, M. A. (2004), "Economic Analysis and the Formulation of U.S. Climate Policy", in *Painting the White House Green: Rationalizing Environmental Policy Inside the Executive Office of the President*, R. Lutter and J. F. Shogren (eds.), Resources for the Future, Washington DC.

United Nations (2004), "World Population Prospects: The 2004 Revision and World Urbanization Prospects", Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, New York.

US EPA (2006), "Global Mitigation of Non-CO2 Greenhouse Gases", United States Environmental Protection Agency, Office of Atmospheric Programs, Washington DC.

van Vuuren, D., den Elzen, M., Berk, M. and de Moor, A. (2002), "An evaluation of the level of ambition and implications of the Bush Climate Change Initiative", *Climate Policy* 2(4): 293-301.

Weitzman, M. L. (1974), "Prices vs Quantities", *The Review of Economic Studies* 41(4): 477-491.

Weyant, J. (1999), "The costs of the Kyoto Protocol: a multi-model evaluation", *The Energy Journal, Special Issue*.

WRI (2005), "Climate Analysis Indicator Tool", version 3.0, World Resources Institute, Washington DC.