

Optimal intensity targets  
for emissions trading under uncertainty

Frank Jotzo and John C.V. Pezzey

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Frank Jotzo and John C.V. Pezzey<sup>1,2</sup>

Centre for Resource and Environmental Studies  
Australian National University, Canberra, ACT 0200, Australia  
E-mail: frank.jotzo@anu.edu.au and pezzey@cres.anu.edu.au

## *Abstract:*

Uncertainty can hamper the stringency of 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 a post-Kyoto international greenhouse emissions trading scheme. 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 2020 global cap-and-trade treaty under multiple uncertainties and endogenous commitments, we estimate that optimal intensity targets could achieve global abatement as much as 20 per cent higher than under absolute targets, and even greater increases in welfare measures. 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 cases. Although target indexation is no magic wand for a future global climate treaty, gains from reduced cost uncertainty might justify increased complexity, framing issues and other potential downsides of intensity targets.

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

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## Table of contents

1. Introduction .....	1
2. Empirical background for intensity targets .....	4
2.1 The GDP-emissions link .....	4
2.2 Magnitude of uncertainties .....	5
3. Theory of intensity targets .....	7
3.1 Future emissions and uncertainties .....	7
3.2 Emissions targets .....	8
3.3 Optimal intensity targets .....	9
3.4 Does GDP indexation reduce uncertainty? .....	10
4. The MAGES model for emissions trading with flexible targets .....	11
4.1 Abatement costs and benefits, and permit trading .....	11
4.2 Payoff and risk aversion .....	13
4.3 Optimality, the equity criterion, and endogenous targets .....	15
4.4 Calibration of benefit and risk aversion parameters .....	16
5. Performance of intensity targets .....	17
5.1 Reference Case with absolute targets .....	17
5.2 Intensity targets with fixed levels .....	20
5.3 Endogenous intensity targets .....	21
5.4 Optimal intensity targets by country .....	23
5.5 Alternative scenarios and sensitivity analysis .....	26
6. Applicability and drawbacks of target indexation .....	29
6.1 Pro-cyclical effects and framing of uncertainty .....	29
6.2 Shifting uncertainty to emission levels .....	30
6.3 Complexity and window-dressing .....	30
6.4 Intensity targets for developing countries in a post-Kyoto treaty .....	31
7. Conclusions .....	33
Appendix: Calibration of the MAGES-GHG model .....	35
Notes on calibration .....	35
References .....	38

## 1. Introduction

Uncertainty can be a major impediment for cap-and-trade schemes for tradeable 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 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. Apart from global equity issues and the 'blame game' over who should take greenhouse action – with the USA demanding participation of major developing countries from the outset, but China, India and others insisting that rich countries have an obligation to act first – uncertainty continues to be one of the largest stumbling blocks hampering a global climate agreement. 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' decisionmakers can ill afford to sign a treaty that risks major cost blow-outs or 'stifling development'.

It is well established that on theoretical grounds, price control is preferable to quantity control under cost uncertainty and for pollutants with a flat marginal damage function, such as greenhouse gases (Weitzman 1974, Pizer 2002). Nevertheless, cap-and-trade is fast becoming the dominant instrument for limiting greenhouse gas emissions both within countries and internationally. The European CO<sub>2</sub> emissions trading scheme is the largest commitment to this instrument so far, and a number of US States are considering their own cap-and-trade systems. The Kyoto Protocol is widely seen as a useful point of departure for future international climate policy future (Böhringer 2003), and institutional restrictions may work against emissions taxes at the international level (Endres and Finus 2002). Emissions targets and trading are the likely starting point for the next round of global climate negotiations. Looking beyond greenhouse gases, permit trading is increasingly used for many other pollutants, from

sulphur dioxide to freshwater quality (Stavins 2003), and cost uncertainty is an issue in practically all of these schemes.

Can cap-and-trade schemes be better designed to reduce uncertainty, and so make environmental agreements more achievable and pave the way for more stringent commitments? Several design features have been proposed to reduce uncertainty, among them making targets more flexible by indexing target allocations to GDP, thus making them targets for the emissions/GDP ratio or *emissions intensity*. An intensity target can also be interpreted as a conventional, absolute target with an ex-post adjustment. If GDP turns out higher than expected, more permits are issued; if it is lower than anticipated, the permit allocation is reduced; if expectations are met, it is equivalent to an absolute target. Intensity targets (also referred to as 'relative', 'rate-based', or 'dynamic' targets) are thus designed to compensate for fluctuations in emissions that are caused by fluctuations in economic activity. Note that we discuss intensity targets as a means of introducing flexibility to a quantitative target at some point in time, as distinct from emissions intensity an alternative way of framing long-term pathways for greenhouse emissions.

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.<sup>3</sup> The Bush administration, after rejecting the Kyoto Protocol, 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 concept of intensity targets – and also brought a greater political dimension to what is essentially a technical issue of mechanism design.<sup>4</sup> Variants of intensity targets ('ex-post adjustments') were also proposed by several European governments for domestic permit allocation under the EU CO<sub>2</sub> trading scheme, but were not implemented.

In the emerging literature on intensity targets, Ellerman and Sue Wing (2003) discussed some basic properties, including that intensity targets may perform better if they are indexed partially to GDP, rather than one-to-one. In a yet unpublished paper, they spelt out formal conditions under which intensity targets reduce the difference between expected and realised abatement burden (Sue Wing et al. 2005). Their analysis is for single countries, so transmission of uncertainty through permit trading is not considered. From empirical tests of these conditions using historical data, they

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<sup>3</sup> 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.

<sup>4</sup> On the Bush 'target', see van Vuuren et al. 2002, Pew Center 2003, Blanchard and Perkaus 2004, Aldy 2004, and Pizer 2005; and on ex-post adjustments under EU emissions trading, see Schleicher and Betz 2005.

concluded that intensity targets would have outperformed absolute targets in many (especially less developed), but not all countries, and that partially indexed intensity targets would have been preferred in general.

Another relevant, as yet unpublished study is that by Quirion (2003) who used an analytic single-region model with two uncertainties to compare absolute and intensity targets as well as price-based emissions control. He concluded that for many parameter constellations, intensity targets would be dominated by either taxes or absolute targets; but that for the greenhouse case (where the marginal benefit curve is flat), intensity targets could be an interesting second-best option if an international tax is politically infeasible. Kolstad (2005) made a theoretical argument that intensity targets could reduce cost uncertainty.

Criticisms of the concept of an intensity target include its greater complexity, that GDP may be problematic as an index, and that allowable emissions levels under a treaty become uncertain (Müller and Müller-Fürstenberger 2003, Dudek and Golub 2003). A different strand of the literature has pointed out that linking permit allocation to output removes incentives to cut back output to achieve abatement, and can thus lead to inefficiencies (see Fischer 2003, Gielen et al. 2002). We contend that this is an issue for firm-level rather than for national targets, as reducing national output would generally not be a policy choice for meeting a national greenhouse target. Potential drawbacks of intensity targets are discussed in more detail in Section 6 of this paper.

Here, we construct a general, variable intensity target under multiple uncertainties about future emissions, provide some empirical foundations, and derive a simple rule for optimal GDP indexation of emissions targets. We then present what we believe is the first *multi*-country empirical modelling analysis of emissions targets and trading under uncertainty, with feedback between mechanism design and stringency of environmental commitments. We use a 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, see Pezzey and Jotzo 2005 – henceforth referred to as PJ). Our model includes three types of future emissions uncertainties, the benefits and (uncertain) costs of emissions abatement and trading, and risk aversion with regard to countries' expected payoff from an international treaty. The model allows to compute optimal targets that are endogenous to the parameters and policy mechanisms chosen. Here, the model is calibrated as an 18-region model of a cooperative (non-free-riding) post-Kyoto treaty for all countries and most greenhouse gas emissions in 2020 (MAGES-GHG).

We begin in Section 2 by discussing some findings on the empirical underpinnings of intensity targets, namely the linkage between fluctuation in GDP and in emissions, as

well as the relative magnitude of uncertainties about emissions, GDP and emissions intensity. Section 3 sets out the theory of intensity targets and derives our rule for optimal indexation. Section 4 gives a brief description of the principles and calibration of the model (with more detail in the Appendix). Simulation results and sensitivity analysis are presented in Section 5, 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: Section 6 concludes.

## **2. Empirical background for intensity targets**

Is there a link between fluctuations in economic activity and fluctuations in emissions? What is the relative magnitude of uncertainties about future greenhouse gas emissions, GDP and emissions intensity of output? These questions determine whether emissions intensity targets, which link emission targets to future economic growth, can help reduce uncertainty in permit markets. Here we briefly explore some empirical evidence, which is later used to formulate and calibrate our model.

### *2.1 The GDP-emissions link*

The concept of intensity targets as a means to reduce uncertainty rests on the assumption that GDP and emissions tend to move together. Intensity targets would link the permit allocation to realised GDP levels in order to provide a more lenient target if GDP grows fast, and a more stringent target if economic growth is slow. Thus whether and to what degree emissions depend on economic activity as measured by GDP determines whether intensity targets can perform better than absolute targets, and to what degree the target should be indexed to GDP.

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. 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.

Several unpublished studies have provided empirical evidence on the GDP-emissions relationship in the context of intensity targets, though mostly for small samples. Philibert (2004) constructed a set of 'forecasting errors' for emissions and GDP from a one-period linear extrapolation model applied to historical data. A positive relationship is evident between forecasting errors in emissions and in GDP; however, in that sample only a small share of variability in emissions is explained by variability in economic growth. Höhne and Harnisch (2002) looked at fluctuations in GDP and

emissions over time, and detected a relationship between energy sector emissions and GDP in three out of the four countries considered. Sue Wing et al. (2005) examined emissions forecasts and historical data for a number of countries. They found a positive correlation between GDP and emissions in most cases, in particular in developing countries; while variability was sometimes greater in emissions, sometimes in GDP. Considered together with how stringent emissions reductions would be, this leads to intensity targets being preferred over absolute targets in most but not all cases, in their analysis. In the published literature, Lutter (2000) found support for a statistical model where emissions growth depends on lagged GDP growth, using panel data of historical CO<sub>2</sub> emissions and GDP. Kim and Baumert (2002) identified a close connection between CO<sub>2</sub> emissions and GDP in Korea, while Bouille and Girardin (2002) concluded that greenhouse emissions in Argentina were linked with GDP only in certain sectors of the economy.

Our own empirical work, using historical data for a large sample of countries, confirms the finding that fluctuations in GDP tend to be associated with fluctuations in emissions from fossil fuel combustion. Tracking both variables over time (1971–2000) shows a significant positive correlation between the deviation of GDP from its trend and emissions from their trend, for 23 out of the 30 largest emitting countries. The strength of the correlation varies, with a mean and median around one. In other words, emissions on average tended to move in tandem with GDP, but with large divergences from the mean in individual episodes due to changes in emissions intensity.

Does such a link also hold for emissions other than from fossil fuel combustion? Data for non-CO<sub>2</sub> emissions is available only for some years, so we assessed this question by constructing 'forecasts' using historical data for a large number of countries. There is a significant positive correlation between forecast errors for GDP and for energy sector CO<sub>2</sub> emissions (as found by Philibert), but no correlation is evident for emissions of methane, nitrous oxide and CO<sub>2</sub> from land-use change.

## 2.2 *Magnitude of uncertainties*

Intensity targets will only be able to deal with GDP-related uncertainty, not uncertainty about future emissions intensity, or uncertainty in parts of the economy where emissions are independent of GDP. So to assess the magnitude of potential improvements from intensity targets, the relative magnitude of these uncertainties is crucial.<sup>5</sup>

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<sup>5</sup> Throughout, we treat 'uncertainty' as the same, quantifiable concept as 'risk', rather than Knightian (unquantifiable) uncertainty.



The literature provides no systematic comparison of these uncertainties. We assessed them by again constructing 'forecasts' on the basis of historical data, comparing forecasts for the year 2000 made on the basis of information available in 1985. Done for a large sample of countries, this yields a distribution of forecast errors, the standard deviation of which can serve as a proxy for the magnitude of uncertainty. Uncertainty was estimated in this way for GDP, energy sector emissions, energy sector emissions intensity, and non-energy sector emissions; and separately for OECD and non-OECD countries.

The results indicate that uncertainty about future GDP is sizeable, but significantly smaller than uncertainty about emissions and emissions intensity. This is confirmed by an analysis of forecast errors by the International Energy Agency and the US Energy Information Administration for a number of countries over the period 1995–2000. 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 from fuel combustion. Appendix Table A1 gives the estimated standard deviations, which are used as parameter values in the MAGES-GHG model.

In our model, we will be making the assumption that realizations of random variables are independent of each other, in particular that deviations in emissions intensity in the energy sector from their expectation are independent of GDP deviations. This independence assumption is supported by results from the statistical analysis.

### 3. Theory of intensity targets

Here we present a formulation of future business-as-usual (BAU) emissions as a function of three separate uncertainties, informed by the empirical findings discussed above. This is complemented by a generalized formulation of GDP-indexed emission targets. We 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.

#### 3.1 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:

- uncertainty in output, measured by GDP and denoted  $Y_i$  \$/yr (where \$ means constant 2000 US dollars)
- uncertainty in emissions intensity of output in the 'linked' part of the economy, denoted  $\eta_i$  t/\$ (where t means a tonne of CO<sub>2</sub>-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

$$\tilde{E}_i^b = E_i^b [1 + \alpha_i (\varepsilon_{Y_i} + \varepsilon_{\eta_i}) + (1 - \alpha) \varepsilon_{\rho_i}] \quad [3.1]$$

where

$\tilde{E}_i^b$	Actual BAU emissions in a particular random realization (in t/yr)
$E_i^b$	Expected BAU emissions
$\alpha_i$	Fixed share of the economy where emissions are linked with GDP ( $0 \leq \alpha_i \leq 1$ )
$\varepsilon_{Y_i}$	Deviation ('error') of actual GDP from its expectation
$\varepsilon_{\eta_i}$	Deviation of actual emissions intensity from its expectation in the 'linked' sector
$\varepsilon_{\rho_i}$	Deviation of actual emissions from expectations in the 'non-linked' sector.

Throughout this paper, a tilde  $\sim$  superscript denotes a particular realization of a random variable; whereas no superscript denotes the expectation of a random variable, or a

parameter. And the disappearance of subscript  $i$  or  $k$  denotes summing over all countries:  $\sum_i J_i = \sum_k J_k =: J$ , for any variable or parameter  $J$ .

Error terms  $\varepsilon_{Y_i}$  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

$$\varepsilon_{Y_i} \sim N(0, \sigma_{Y_i}), \quad \varepsilon_{\eta_i} \sim N(0, \sigma_{\eta_i}), \quad \text{and} \quad \varepsilon_{\rho_i} \sim N(0, \sigma_{\rho_i}). \quad [3.2]$$

So GDP uncertainty  $\varepsilon_{Y_i}$  affects emissions in the  $\alpha$  part of the economy, but structural shifts and other random influences ( $\varepsilon_{\eta_i}$ ) also play a role here; while in other parts of the economy ( $1-\alpha$ ), emissions are completely independent of GDP and subject to random shocks  $\varepsilon_{\rho_i}$ .

The  $\sigma$  parameters are measures of the degree of uncertainty. For numerical calibration, we use empirical estimates of the standard deviation of forecast errors for each variable described above. Uncertainty about emissions intensity is greater than about GDP ( $\sigma_{\eta_i} > \sigma_{Y_i}$ ), uncertainty in non-OECD (developing, or 'Southern' countries) is greater than in rich ('Northern') countries, and uncertainty in the non-linked sector ( $\sigma_{\rho_i}$ ) is of broadly the same magnitude as that for emissions intensity in the linked sector, but depends on the particular composition of emissions in each country or region.

Again following empirical findings, we assume that the share  $\alpha_i$  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. Expected BAU emissions  $E_i^b$  are calibrated on the basis of levels reported for the year 2000, forecasts by the main energy forecasting agencies, and trend extrapolation for non-energy sector emissions. GDP ( $Y_i$ ) and population ( $L_i$ ) are calibrated to recent data, projections and estimates from the literature. The Appendix gives sources and shows all parameter values used.

### 3.2 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.

The (realised) emissions target is

$$\tilde{X}_i = x_i E_i^b (1 + \beta_i \varepsilon_{Y_i}) \quad [3.3]$$

with

$\tilde{X}_i$  realised target (in t/year)

$x_i$  relative target, as a share of expected future BAU emissions

$\beta_i$  degree of indexation of the target to GDP ( $\beta_i \geq 0$ )

and  $\tilde{E}_i^b$  and  $\varepsilon_{Y_i}$  are as defined above.

By how much the target gets adjusted for a deviation in GDP from its expected value depends on whether and to what degree targets are indexed. Two obvious special cases are

*Absolute target*, with no indexation ( $\beta_i = 0$ ), hence  $\tilde{X}_i = X_i = x_i E_i^b$ ; [3.4]

*Standard intensity target*, with one-to-one indexation ( $\beta_i = 1$ ), hence  $\tilde{X}_i = x_i E_i^b (1 + \varepsilon_{Y_i})$ . [3.5]

So in our terminology, Kyoto Protocol targets are absolute; and what the literature usually refers to as 'intensity targets' are standard intensity targets with one-to-one indexation.

Partial indexation would of course be possible and is discussed below. Importantly, without GDP uncertainty, absolute and intensity targets are the same because they use the same  $x_i$ ; the popular view that intensity targets are inherently less stringent than absolute targets is thus unjustified.

### 3.3 Optimal intensity targets

Since the error term  $\varepsilon_{Y_i}$  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):

$$\tilde{E}_i^b - \tilde{X}_i = E_i^b - X_i + \tilde{N}_{E_i}, \text{ hence } \tilde{E}^b - \tilde{X} = E^b - X + \tilde{N}_E, \quad [3.6]$$

where a country's net emissions uncertainty (net of any neutralising effect of the index  $\beta_i$ ) is

$$\tilde{N}_{E_i} := [(\alpha_i - \beta_i x_i) \varepsilon_{Y_i} + \alpha_i \varepsilon_{\eta_i} + (1 - \alpha_i) \varepsilon_{\rho_i}] E_i^b. \quad [3.7]$$

The expectation of squared net emissions uncertainty is also important:

$$D_{E_i} := E[\tilde{N}_{E_i}^2] = [(\alpha_i - \beta_i x_i)^2 \sigma_{Y_i}^2 + \alpha_i^2 \sigma_{\eta_i}^2 + (1 - \alpha_i)^2 \sigma_{\rho_i}^2] E_i^{b^2}. \quad [3.8]$$

The expected global net benefit of abatement is maximised when squared net emissions uncertainty  $D_{E_i}$  is minimised for all countries (as shown in PJ). This occurs when GDP-related uncertainty  $\sigma_{Y_i}$  is fully neutralised, which is achieved by setting  $\beta_i$  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

$$\beta_i^* = \alpha_i / x_i \text{ for all } i. \quad [3.9]$$

Thus, the optimal degree of indexation depends on the share of total emissions linked with GDP, as well as the relative stringency of the target commitment.

This allows us to define an

$$\text{Optimal intensity target with } \tilde{X}_i = x_i E_i^b [1 + (\alpha_i / x_i) \varepsilon_{y_i}] . \quad [3.10]$$

For some countries, the share of emissions linked with GDP  $\alpha_i$  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 other recent work.<sup>6</sup> Our simple formula for optimal indexation should help bring conceptual clarity, including about bounds for indexation: optimal target design may well imply super-indexation, and there is no reason why indexation should be capped at a factor of one.

### 3.4 Does GDP indexation reduce uncertainty?

From [3.8], target indexation reduces uncertainty  $D_{E_i}$  if

$$(\alpha_i - \beta_i x_i)^2 < \alpha_i^2 \quad [3.11].$$

So from [3.10], 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  $\beta_i = 1$ , [3.11] holds whenever

$$(0 <) x_i < 2\alpha_i , \quad [3.12]$$

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

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<sup>6</sup> In a rather different analytical framework, Sue Wing et al. (2005, p.27) 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."

#### 4. The MAGES model for emissions trading with flexible targets

To simulate the performance of intensity targets, we use the MAGES (Mechanisms for Abating Global Emissions under Stochasticity) model, a new partial equilibrium, stochastic model of global emissions trading under uncertainty. The model includes representation of uncertain future emissions and flexible targets as described in Section 3, costs and benefits from emissions abatement and trading, and risk aversion that influences countries' decisions about the stringency of commitments that they are willing to take on. Expectations of random variables are computed algebraically, rather than approximated through repeated runs of a deterministic model, allowing numerical optimisation in the simulation model.

In this application, the model is calibrated for a global, post-Kyoto climate treaty, covering all greenhouse gases and taking effect in the year 2020 – this calibration we refer to as MAGES-GHG. We have chosen to divide the world into 18 regions or countries, just known as '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.

Here we briefly describe the structure of the model and its empirical calibration for the global greenhouse case. For more detail on conceptual and theoretical underpinnings of the MAGES model, see PJ; and for details on the empirical calibration of MAGES-GHG, again see the Appendix.

##### 4.1 Abatement costs and benefits, and permit trading

The abatement treaty grants a flexible permit allocation  $\{\tilde{X}_i\}$  defined in [3.3] to all countries. Perfect enforcement in the global permit market makes abated emissions equal the target only globally:

$$\tilde{E} = \tilde{X}, \text{ hence global abatement } \quad \tilde{Q} = \tilde{E}^b - \tilde{X}. \quad [4.1]$$

The market price of a permit is  $\tilde{p}$ , and a country's emissions trading (ET) revenue is

$$\tilde{R}_i := \tilde{p}[\tilde{X}_i - \tilde{E}_i^b + \tilde{Q}(\tilde{p})], \text{ with } \tilde{R} \equiv 0 \text{ automatically.} \quad [4.2]$$

Country  $i$ 's *net benefit* from ET compared to no abatement anywhere<sup>7</sup> is defined as

$$\tilde{A}_i \quad := \tilde{B}_i - \tilde{C}_i \text{ \$/yr, where} \quad [4.3]^8$$

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<sup>7</sup> By comparing ET 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 4.3 below.

$$\tilde{B}_i(\tilde{Q}) \quad := V_i\tilde{Q} - \frac{1}{2}W_i(\tilde{Q})^2 + \tilde{R}_i, \quad V_i \text{ \$/t} > 0, \quad W_i \text{ \$/yr/t}^2 > 0, \quad [4.4]$$

is  $i$ 's dollar-valued benefit  $\tilde{B}_i$  of global abatement  $\tilde{Q}$ , including its ET revenue. We include valuation of (or benefits from) global abatement in order to be able to determine the optimal level of abatement, in the vein of the RICE model (Nordhaus and Yang 1996).

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

$$\begin{aligned} \tilde{C}_i(\tilde{Q}_i) &:= \frac{1}{2}\tilde{Q}_i^2/M_i + \tilde{Q}_i\varepsilon_{Ci} \\ &= \frac{1}{2}\tilde{Q}_i^2/M_i + \tilde{Q}_i\tilde{N}_{Ci}/M_i, \quad \text{with } \tilde{N}_{Ci} := M_i\varepsilon_{Ci}. \end{aligned} \quad [4.5]$$

The marginal abatement cost (MAC) curve is then linear<sup>9</sup>, and uncertain:

$$\tilde{C}'_i(\tilde{Q}_i) = \tilde{Q}_i/M_i + \varepsilon_{Ci}, \quad [4.6]$$

Here  $\varepsilon_{Ci}$  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  $\varepsilon_{Ci}$  is independent of all other uncertainties.<sup>10</sup> Hence from [4.3], [4.4] and [4.5], realised net benefit is

$$\tilde{A}_i = V_i\tilde{Q} - \frac{1}{2}W_i(\tilde{Q})^2 + \tilde{R}_i - \frac{1}{2}\tilde{Q}_i^2/M_i - \tilde{Q}_i\tilde{N}_{Ci}/M_i. \quad [4.7]$$

A similar formula applies to the Unilateral case, denoted by the superscript  $U$ . Under unilateralism, each country decides on its own abatement effort in isolation, and there is no trading revenue:

$$\tilde{A}_i^U := V_i\tilde{Q}^U - \frac{1}{2}W_i(\tilde{Q}^U)^2 - \frac{1}{2}(\tilde{Q}_i^U)^2/M_i - \tilde{Q}_i^U\tilde{N}_{Ci}/M_i. \quad [4.8]$$

We do not model uncertainties in the benefit 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). 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 reason for such correlation in the greenhouse case.

The abatement potentials  $\{M_i\}$  in [4.5] are calibrated for energy-derived CO<sub>2</sub> on the basis of structural characteristics of each country, and these relationship in turn are taken

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<sup>8</sup> 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.

<sup>9</sup> The assumption of quadratic cost curves and thus linear MACs is necessary to keep the stochastic analysis tractable. Unless levels of abatement are very high (which they are not in our empirical application), such linearisation does not greatly change estimates of total costs compared to empirically estimated MAC functions with a typical degree of convexity.

<sup>10</sup> 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.

from published results from computable general equilibrium models; while parameters for abatement costs outside the energy sector are calibrated with reference to other studies (see Appendix). The degree of uncertainty about abatement costs  $\{\sigma_{Ci}\}$  can be gleaned by comparing MAC estimates from different models (Weyant 1999), indicating substantial uncertainty about abatement opportunities and costs. Calibration of the benefit parameters  $\{V_i\}$  and  $\{W_i\}$  in [4.4] is discussed further below.

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

$$\tilde{Q}_i = \tilde{p}M_i - \tilde{N}_{Ci}, \text{ and hence} \quad [4.9]$$

$$\tilde{p} = (E^b - X + \tilde{N}_E + \tilde{N}_C)/M, \text{ with expectation} \quad [4.10]$$

$$p = (E^b - X)/M. \quad [4.11]$$

[4.10] 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.

## 4.2 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 as the difference in realised net benefits:

$$\tilde{G}_i := \tilde{A}_i - \tilde{A}_i^U \quad [4.12]$$

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

$$\tilde{U}_i := \tilde{G}_i + z_i(1 - e^{-r\tilde{G}_i}) \text{ \$/yr}; \quad z_i \text{ \$/yr} > 0, \quad r \text{ yr/\$} > 0. \quad [4.13]$$

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.

Finally, its *expected payoff* is then, since all the errors have normal distributions with zero means,

$$U_i := \int_{\mathbf{R}^{4n}} [\tilde{G}_i(\varepsilon) + z_i(1 - e^{-r\tilde{G}_i(\varepsilon)})] [e^{-1/2\Sigma[(\varepsilon_{Yi}/\sigma_{Yi})^2 + (\varepsilon_{\eta i}/\sigma_{\eta i})^2 + (\varepsilon_{\rho i}/\sigma_{\rho i})^2 + (\varepsilon_{Ci}/\sigma_{Ci})^2]} / (2\pi)^{2n} \Pi(\sigma_{Yi}\sigma_{\eta i}\sigma_{\rho i}\sigma_{Ci})] d\varepsilon, \text{ with}$$



$$\varepsilon := (\varepsilon_{Y_1}, \dots, \varepsilon_{Y_n}, \varepsilon_{\eta_1}, \dots, \varepsilon_{\eta_n}, \varepsilon_{\rho_1}, \dots, \varepsilon_{\rho_n}, \varepsilon_{C_1}, \dots, \varepsilon_{C_n}). \quad [4.14]$$

This will be less than expected gain  $G_i$ , by virtue of the positive parameters  $z_i$  and  $r$ . Importantly, the characterisation in [4.12]-[4.14] 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 6.1.

Country  $i$ 's expected (risk-adjusted) payoff from ET instead of Unilateralism, showing functional dependences only on policy choice parameters  $\mathbf{x} := \{x_i\}$  and  $\boldsymbol{\beta} := \{\beta_i\}$ , and uncertainty measures  $\boldsymbol{\sigma} = \{\sigma_{Y_i}, \sigma_{\eta_i}, \sigma_{\rho_i}, \sigma_{C_i}\}$  can then be shown to be (see PJ):

$$U_i(\mathbf{x}, \boldsymbol{\beta}, \boldsymbol{\sigma}) \approx \tilde{A}_i + F_i - A_i^U + z_i(1 - e^{1/2 r^2 \Gamma_i - r(\tilde{A}_i + F_i - A_i^U)}), \quad [4.15]^{11}$$

where

$$\tilde{A}_i(\mathbf{x}) := V_i p M + 1/2 p^2 (M_i - W_i M^2) - p(1 - x_i) E_i^b \text{ \$/yr}; \quad [4.16]$$

$$F_i(\mathbf{x}, \boldsymbol{\beta}, \boldsymbol{\sigma}) := - (1/M) D_{E_i} - 1/2 (W_i - M_i / M^2) D_E + [(1/2 M_i) - 1/M] D_{C_i} + 1/2 (M_i / M^2) D_C; \quad [4.17]$$

$$A_i^U(\boldsymbol{\sigma}) := V_i Q^U - 1/2 W_i (1 + W_i M_i) [(Q^U)^2 + D_C / (1 + \Sigma W_k M_k)^2] - 1/2 V_i^2 M_i + 1/2 D_{C_i} / M_i + 1/2 V_i W_i M_i Q^U - 1/2 W_i D_{C_i} / (1 + \Sigma W_k M_k), \quad [4.18]$$

$$\text{with } Q^U := \Sigma V_i M_i / (1 + \Sigma W_k M_k); \quad [4.19]$$

$$\Gamma_i(\mathbf{x}, \boldsymbol{\beta}, \boldsymbol{\sigma}) := (p - H_{E_i})^2 D_{E_i} + H_{E_i}^2 \Sigma_i D_{E_k} + (p - H_{C_i})^2 D_{C_i} + H_{C_i}^2 \Sigma_i D_{C_k}, \quad [4.20]$$

$$\text{with } H_{E_i}^T(\mathbf{x}) := (p^T M_i - E_i^b + X_i) / M + V_i - W_i p^T M \text{ \$/t}, \quad [4.21]$$

$$H_{C_i}^T(\mathbf{x}) := (p^T M_i - E_i^b + X_i^T) / M \text{ \$/t}, \quad [4.22]$$

and  $p = (E^b - X) / M$  as in [4.11].

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<sup>11</sup> The approximation here arises from using the expectation  $F_i$  instead of its realisation value  $\tilde{F}_i$  (not shown here) in the exponent of the expectation integral [4.14], in order that the integral can be computed analytically; and from using the expectation  $A_i^U$  instead of both occurrences of its realisation  $\tilde{A}_i^U$  in [4.14]. As explained in PJ, the approximation is acceptable for the purpose here, particularly as we infer risk aversion parameters (see below) and this inference incorporates the approximation in [4.15].

### 4.3 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*, subject to: [4.23]

– 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. [4.24]

The *Reference Case*, to which results for all other scenarios will be compared, is the outcome of applying [4.23] and [4.24] to emissions trading with absolute targets. In simulations with optimal intensity targets, we jointly optimise targets  $x_i$  and indexation  $\beta_i$ .

Criterion [4.24] does not specify a direct rule for target distribution; so under a target type that neutralises some of the uncertainty, payoff will be greater. In turn this leads to more abatement by way of tighter targets (a lower  $X$ ), i.e. *endogenous targets*. 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 are *exogenous* to the choice of abatement mechanism; and none depend on the degree of uncertainty that countries are exposed to. In our analysis, both the overall stringency of the treaty and the differentiation of commitments between countries are endogenous and differ according to target type, parameters and the simulation scenario chosen. We can thus model how better mechanism design may affect environmental outcomes from a treaty.

An egalitarian criterion such as [4.24] may seem unrealistic in terms of international politics. However, in sensitivity analysis in Section 5, we find the choice of equity criterion makes little difference to the relative merits of absolute and intensity targets. Equity constraints are fulfilled solely through adjusting targets  $x_i$ , which we feel politically more realistic than cash transfers, as assumed for example by Bohm and Carlén (2002).

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 ( $U_i > 0$ ), which in practice is satisfied for all simulations. This is conceptually different from the more demanding 'no-free-ride' condition, which underlies the generally pessimistic results from non-cooperative models of multi-party environmental treaties (Carraro and Siniscalco 1993, Barrett 1994). Instead, we have implicitly assumed that political factors can prevent free-riding (Eckersley 2004). A similar approach of modelling permit allocations that fulfil individual rationality in the sense of each party being better off than in the non-cooperative state, while not preventing free-riding as such, was taken by Germain and Van Steenberghe (2003). The MAGES model can be

extended to non-cooperative situations and to analyse free-riding incentives, but this is left for further work.

#### 4.4 Calibration of benefit and risk aversion parameters

The valuation parameters  $\{V_i\}$  are calibrated in order to conform with broad observations about the international debate about burden sharing. As explained further in the Appendix, *relative* per capita valuations  $\{V_i/L_i\}$  are assumed to be a function of per capita income and historical responsibility for greenhouse emissions, yielding much higher  $\{V_i/L_i\}$  in rich countries, but roughly an even split in total valuation  $V$  between North and South, broadly in line with climate change damage estimates from the literature.  $W_i$ , the slope of the GHG marginal benefit 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 due to the nature of greenhouse gases as a long-lived stock pollutant, the marginal damage curve is almost flat (Pizer 2002). Overall global valuation parameters  $V$  and  $W$  are chosen so that a global climate treaty results in a halving of global emissions growth between 2000 and 2020, compared to BAU emissions growth, in our Reference Case scenario.

In calibrating the risk aversion parameters  $\{z_i\}$  and  $r$  in [4.13], we first choose all  $z_i = z/y_i$ , for some constant  $z$  and  $y_i = Y_i/L_i$ , per capita GDP. The  $1/y_i$  factor matches the stylised fact that uncertainty matters more in poor countries, and serves our purpose to capture the essential features of the global climate policy debate and broad differences across countries. Parameters  $z$  and  $r$  are then calibrated so that risk aversion results in significantly less stringent commitments under uncertainty, but without stifling agreement altogether. In the default calibration  $z = 1$ ; while  $r$ , the payoff concavity parameter, is chosen so that global abatement in the Reference Case is *one third* lower than it would be without risk aversion.

A more comprehensive approach to calibrating both benefit and risk aversion parameters might be a survey of expert opinion in each country along the lines of Weitzman (2001), but that remains for further work.

## 5. Performance of intensity targets

The theoretical analysis modeled how optimal intensity targets reduce uncertainty and improve a treaty's environmental outcome as well as the payoff to participating countries, while standard intensity targets may or may not reduce uncertainty. But how large are the potential improvements? 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 the MAGES-GHG 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.

### 5.1 Reference Case with absolute targets

The Reference Case assumes that all countries participate in a cap-and-trade agreement with absolute targets (no indexation,  $\beta_i = 0$ ), covering all greenhouse gas emissions. Like all other scenarios, the absolute emission targets used for the reference scenario are chosen to satisfy [4.23] and [4.24], that is to maximise expected global (risk-adjusted) payoff from a full ET treaty subject to per capita payoff being equalised across all countries. The reference scenario is not meant as a prediction of what a future climate treaty would look like, but merely as a point of comparison for alternative target types.

Global abated emissions ( $E$ ) in the Reference Case grow by 16% from 2000 to 2020, compared to a projected increase of 32% ( $E^b$ ) under BAU. 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 not wholly unrealistic level of effort for a post-Kyoto climate treaty. The expected amount of abatement undertaken under the treaty is 6.5 Gt/yr, which compares to expected abatement in the unilateral case of around 1 Gt/yr, calculated from [4.19].<sup>12</sup>

The expected permit price  $p$  from [4.11], equal to expected the marginal cost of abatement in all countries, is 15 \$/t, 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<sub>2</sub> emissions trading scheme. Global dollar-valued global gain  $G$  from the climate treaty, defined as the expected sum of

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<sup>12</sup> 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 their abatement action.

[4.12], is 53 billion \$/yr. With risk adjustment, this translates into payoff  $U$  (likewise from [4.13]) of around 44 billion \$/yr. The expected global financial cost of abatement,  $C$  from summing [4.5], is 50 billion \$/year, and thus well below 0.1% of projected global GDP, which reassures us that this is an acceptable application of a partial equilibrium model. Compared to the outcome under certainty equivalence, global abatement (and, by virtue of linear marginal abatement cost curves, the permit price) in the reference scenario is exactly one third lower, reflecting our choice of the risk aversion parameter  $r$ .

**Table I Reference Case: Global results and comparison with certainty equivalence**

	Reference Case: Absolute targets under uncertainty and risk aversion (expectation results)	Certainty equivalence
<i>Expected global values of:</i>		
Target (permits) as share of emissions, $x$	0.88	0.82
Permit price $p$ (\$/t)	15.33	23.00
Abatement $Q$ (Gt/yr)	6.53	9.80
Gain $G$ (G\$/yr)	53.4	100.5
Payoff $U$ (G\$/yr)	44.1	101.2
Note: Gain $G$ and payoff $U$ are defined as improvements compared to the outcome under unilateral action by each country. Results under unilateralism: Net benefit $A^U = 24.5$ G\$/yr, abatement $Q^U = 1.04$ Gt/yr.		

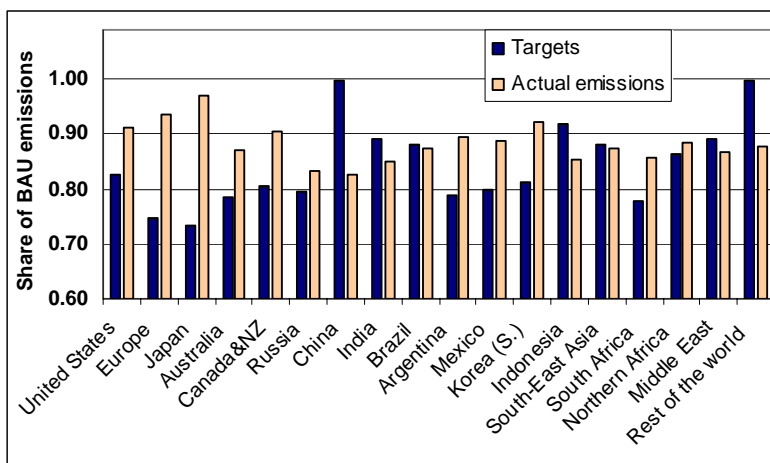
Targets in the reference scenario are strongly differentiated between countries, with stricter targets applying where relative valuation of abatement is higher, abatement is cheaper, and uncertainty or risk aversion lower. On the whole, high-income Northern countries have more stringent relative targets than Southern countries in our Reference Case, as shown in Figure 1. Most Southern countries abate their emissions below their targets, and sell the freed-up permits.

Table II shows a summary of targets and emissions trading flows for the North/South country groups. When expressed as a proportion of base year (2000) emissions, it is evident that Southern countries overall get allocated ‘growth targets’ under our reference scenario, that is, their permit allocation is greater than their current emissions, leaving room for future emissions growth.

The South accounts for over three quarters of global abatement, on account of its greater share in global emissions and higher abatement potential, coupled with our

assumption that all abatement options for all greenhouse gases can be harnessed efficiently – which may be a rather optimistic assumption given real-world institutional constraints and measurement problems (Victor 2001). The South as a group would receive substantial permit revenue, almost offsetting their overall abatement cost.

**Figure 1 Reference Case: Targets and actual emissions after abatement, relative to BAU emissions**



**Table II Reference Case: Targets, abatement and trading**

Region	Target as a share of BAU	Target as share of 2000 emissions	Expected reduction commitment (Gt/yr)	Expected abatement (Gt/yr)	Expected permits sales (Gt/yr)
	$X_i/E_i^b = x_i$	$X_i/E_{i2000}$	$E_i^b - X_i$	$Q_i$	$Q_i - (E_i^b - X_i)$
North	0.79	0.93	3.81	1.40	-2.40
South	0.92	1.30	2.73	5.13	2.40
Global	0.88	1.16	6.53	6.53	0.00

## 5.2 Intensity targets with fixed levels

We model two types of intensity targets and compare them to absolute targets:

- *standard intensity targets* with one-to-one indexation for all countries  $i$ , characterized by one-to-one indexation to GDP ( $\beta_i = 1$  as in [3.5]); and
- *optimal intensity targets*, where  $\beta_i^* = \alpha_i / x_i$  for all  $i$ , so uncertainty due to fluctuations in GDP is fully neutralized, as in [3.10].

In our first set of simulations for both target types, reported in Table III, we hold target levels  $x_i$  (and thereby expected total abatement  $Q$  and the permit price  $p$ ) fixed at Reference Case levels, but introduce target indexation.

The expected global gain  $G$  increases by 13% and 20% respectively under standard and optimal intensity targets for all countries. Expressed in dollar terms, this is equivalent to an increase of up to 10 billion \$/yr – keeping in mind though that estimates of absolute magnitudes depend on our assumptions about the overall extent and ambition of the treaty. Note that this estimated improvement in expected gain under fixed target levels does *not* depend on our assumptions about risk aversion and payoff; it derives directly from reduced cost uncertainty.

Increases in (risk-adjusted) expected payoff  $U$  from target indexation are significantly larger than in gain  $G$ , as they also take account of 'psychological' effects of a reduced risk of incurring losses under emissions trading.

**Table III Exogenous intensity targets: Global results**

	Absolute targets (all $\beta_i=0$ )	Standard intensity targets (all $\beta_i=1$ )	Optimal intensity targets (all $\beta_i^* = \alpha_i/x_i$ )
<i>Expected values of:</i>			
Abatement $Q$ (Gt/yr)	6.53	6.53	6.53
Gain $G$ (billion \$/yr)	53.4	60.2	63.9
Payoff $U$ (billion \$/yr)	44.1	55.6	62.3
<i>Increase compared to absolute targets:</i>			
Abatement $Q$	-	0.0%	0.0%
Gain $G$	-	12.6%	19.6%
Payoff $U$	-	26.0%	41.1%

### 5.3 *Endogenous intensity targets*

Now, we determine target levels endogenously by maximizing global payoff subject to equal per capita distribution of payoffs. With intensity targets neutralizing some or all of the GDP-related uncertainty, greater payoff can be achieved, at a different optimal vector  $\{x_i\}$  of country targets. Importantly, this gives us the chance to assess to what degree reduced uncertainty through more flexible target design might result in more stringent environmental commitments.

Figure 2 shows the connection between target design, payoff and stringency of targets. Expected global payoff (subject to equal per capita payoff) is plotted as a function of expected global abatement, for all three types of targets. Expected payoff is greater under intensity than under absolute targets for any given level of global abatement, and maximum expected payoff is achieved at a greater level of abatement.

With standard intensity targets, expected global abatement increases to 7.2 Gt/yr, from 6.5 to under absolute targets, a 10% increase (Table IV). This improvement of 0.7 Gt/yr is about in the same order of magnitude as total emissions from countries such as Korea, Mexico or Australia. Payoff from the treaty, our main welfare measure, is increased by more than a quarter.

Under optimal intensity targets, significantly bigger improvements are possible, because standard one-to-one indexation will on average over- or undercompensate for fluctuations in GDP. Expected global abatement is 7.7 Gt/yr, around 17% greater than under absolute targets. Expected (risk-adjusted) payoff under optimal intensity targets for all countries is increased by almost half, or around 20 billion \$/yr, compared to without target indexation.

Both payoff and expected gain (not adjusted for risk aversion) are greater under endogenous intensity targets, compared to the corresponding scenarios with fixed targets. This is because in addition to part of the uncertainty being neutralized, the level of abatement is now closer to what it would be under certainty equivalence, which would yield the greatest possible gain.

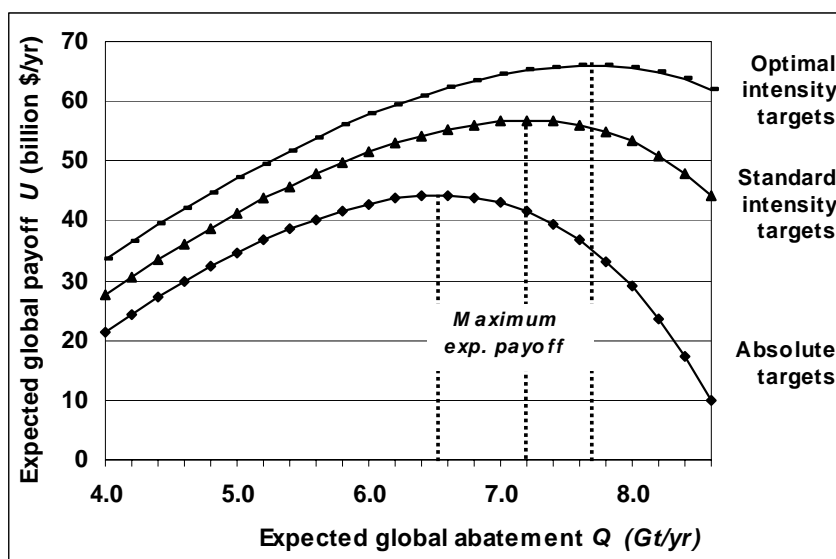
Qualitatively, these results hold also if only some countries take on intensity targets. For example, in a simulation where only Southern, developing countries have (optimal) intensity targets, global abatement is increased by 11% (compared to 17% with optimal indexation for all countries). Reduced uncertainty is transmitted through less variability in the permit price, and under endogenous targets with payoff sharing, all countries benefit from reducing the cost of uncertainty in one part of the world.

These results indicate that intensity targets, particular with optimal indexation, have the potential to boost global abatement, if uncertainty does indeed hamper the



stringency of the commitments that can be agreed upon; and that target indexation could improve welfare even if policymakers were risk-neutral in negotiating a cap-and-trade treaty.

**Figure 2** Expected global payoff as a function of expected global abatement, for three target types



**Table IV** Endogenous intensity targets: Global results

	Absolute targets (all $\beta_i=0$ )	Standard intensity targets (all $\beta_i=1$ )	Optimal intensity targets (all $\beta_i^* = \alpha_i/x_i$ )
<i>Expected values of:</i>			
Abatement $Q$ (Gt/yr)	6.53	7.20	7.66
Gain $G$ (billion \$/yr)	53.4	64.9	71.8
Payoff $U$ (billion \$/yr)	44.1	56.8	66.0
<i>Increase compared to absolute targets:</i>			
Abatement $Q$	-	10.2%	17.2%
Gain $G$	-	21.6%	34.5%
Payoff $U$	-	28.7%	49.6%

#### 5.4 Optimal intensity targets by country

The degree to which intensity targets can help address uncertainty, and consequently make tighter targets possible, differs greatly between countries. Neutralising activity-related emissions uncertainty brings the greatest advantage where the share of emissions linked with GDP ( $\alpha_i$ ) is large, where uncertainty about future GDP ( $\sigma_{y_i}$ ) is large relative to other uncertainties, and where risk aversion ( $z/y_i$ ) is strong. These differences are represented in our multi-region model.

The globally averaged emissions target is 1.2 and 2.1 percentage points more stringent under standard and optimal intensity targets than under absolute targets (Table V). For Southern (mainly developing) countries as a group, the more significant impact comes from moving from standard to optimal intensity targets, rather than moving from absolute to standard intensity targets. The reverse situation applies in Northern countries as a whole. So optimal indexation plays a much more important role in developing than in industrialized countries.

Why is that so? The answer lies in systematic differences in the degree of emissions-GDP linkage  $\alpha_i$  and relative targets  $x_i$  between countries, which enter the optimality condition  $\beta_i^* = \alpha_i / x_i$ . In industrialised countries, fossil fuel combustion – which empirical analysis shows to often be linked with economic activity – typically accounts for a large share of total greenhouse emissions, so  $\alpha_i$  takes on comparatively large values. At the same time, these countries get allocated comparatively stringent targets, so  $x_i$  are low. Together, this tends to result in optimal degrees of indexation  $\beta_i^*$  in the broad vicinity of one; and as a result, standard intensity targets with one-to-one indexation would already do quite well.

The move from absolute to standard intensity targets, and on to optimal intensity targets, leads to slightly less stringent targets (higher  $x_i$ ) in a number of countries, contrary to more stringent commitments in aggregate. This is because reducing the cost of uncertainty has disproportionately large effects in some countries, and these gains are distributed across all countries under our equity rule, by way of adjusting target commitments.

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 1.34 being highest. Australia and Canada/New Zealand, where land-use change and agriculture account for a relatively

large share of total emissions, are exceptions among Northern countries, with optimal indexation below 1.

In most developing countries, partial indexation would be optimal. The degree of optimal indexation varies greatly, particularly in response to the very different emissions profiles found in developing countries. 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 (as low as 0.2), for a treaty that includes all greenhouse gas sources and does not prescribe extremely tight targets for developing countries.

In these countries, the standard  $x_i > 2\alpha_i$ , so from [3.12] 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 intensity targets. In the MAGES-GHG model, 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 – the South-East Asia region.<sup>13</sup> Optimally indexed targets would of course be preferable in all countries.

These results highlight that target indexation must be tailored to individual countries' circumstances in order to maximize the potential for neutralizing uncertainty. Detailed empirical analysis of the link between fluctuations in GDP and fluctuations in emissions, at a disaggregated level in each country, could improve on our comparatively rough estimate of  $\alpha_i$ . Such research would be needed to determine optimal indexation in practice.

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<sup>13</sup> By contrast, Sue Wing et al.(2005) found intensity targets preferable to absolute targets for all six developing countries they looked at. This is largely attributable to the fact that they look at historical data for CO<sub>2</sub> from fossil fuel combustion only, whereas we consider all major greenhouse gas emissions.

**Table V Endogenous targets by country**

Country (N = North)	Reference Case: Absolute targets ( $\beta_i = 0$ )	Standard intensity targets ( $\beta_i = 1$ )	Optimal intensity targets ( $\beta_i^* = \alpha_i/x_i$ )	Indexation under optimal targets	Share of emissions linked with GDP
	<i>Target relative to BAU emissions (<math>x_i</math>)</i>			$\beta_i^*$	$\alpha_i$
United States (N)	0.825	0.782	0.780	1.06	0.83
Europe (N)	0.748	0.720	0.719	1.20	0.86
Japan (N)	0.733	0.723	0.722	1.34	0.97
Australia (N)	0.783	0.785	0.785	0.84	0.66
Canada/NZ (N)	0.807	0.806	0.806	0.76	0.61
Russia	0.796	0.769	0.768	1.18	0.91
China	0.998	0.923	0.920	0.83	0.76
India	0.892	0.909	0.921	0.63	0.58
Brazil	0.882	0.898 *	0.888	0.26	0.23
Argentina	0.788	0.792	0.795	0.60	0.48
Mexico	0.798	0.801	0.805	0.92	0.74
Korea (S.)	0.811	0.805	0.806	1.14	0.92
Indonesia	0.918	0.947 *	0.925	0.19	0.18
South-East Asia	0.881	0.888 *	0.887	0.48	0.43
South Africa	0.779	0.779	0.781	1.14	0.89
Northern Africa	0.862	0.874	0.882	0.78	0.69
Middle East	0.892	0.889	0.891	0.74	0.66
Rest of the world	0.996	1.055 *	1.006	0.32	0.32
<i>Aggregates:</i>					
North	0.790	0.759	0.757	1.10	0.83
South	0.924	0.921	0.909	0.62	0.55
Global	0.879	0.867	0.858	0.78	0.64

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

Optimal target indexation  $\beta_i^*$  for regional aggregates is computed by weighting with BAU emissions  $E_i^0$ .

## 5.5 *Alternative scenarios and sensitivity analysis*

Here we briefly discuss results from alternative scenarios with different assumptions about optimisation objectives and equity rules, and test the sensitivity of results to changes in some key parameters. Together, these analyses show that it is an empirical question by how much intensity targets could improve the outcome from a climate treaty, thus highlighting the need for country-level empirical research in fine-tuning the design of flexible targets. However, the main conclusions about the performance and design of intensity targets are robust.

### *Maximizing additional abatement rather than payoff*

In the scenarios presented above, flexible target design gives greater expected payoff (which is maximized) and hence higher expected global abatement as a corollary. What if instead, countries took expected payoff under absolute targets as a reference point, and channeled all improvements from reduced uncertainty into greater stringency of commitments?

Keeping expected payoff from the agreement fixed at  $U = 44$  as under absolute targets (and applying our equity rule) results in expected abatement  $Q$  of 8.61 and 9.71 under standard and optimal intensity targets respectively. Compared to  $Q = 6.53$  under absolute targets, this means very large increases, of 32% and 49% respectively.

Note that this would *not* be rational optimizing behaviour in the world we model; rather, it is a rough measure of the maximum environmental benefit theoretically attainable from reduced uncertainty. The estimated magnitudes depend strongly on our assumptions about risk aversion.

### *Equity criteria*

As foreshadowed earlier, our choice of equal per capita payoff as our standard equity criterion, as in [4.24], affects target levels and differentiation between countries, but makes little difference to the relative assessment of different types. This is because the impacts of uncertainty get transmitted through adjustments in targets and through the permit price.

For example, changing to a criterion of equal payoff per \$ of GDP, thus giving rich countries a much larger share in total payoff, would result in targets implying a 16% reduction below BAU for North as a country group, and 10% for South (compared to a 21% and 8% reduction respectively in the Reference Case). The increases in global abatement from standard or optimal intensity targets are 9% and 16% respectively under

equal payoff per \$ of GDP (compared to 10% and 17% under our standard assumptions).

### *Uncertainty about GDP*

From [4.15], [4.20] and [3.8], the size of uncertainties about future GDP directly affects the performance of intensity targets compared to absolute targets. To illustrate the impact of GDP uncertainties, the main scenarios were re-run with values of the uncertainty parameter  $\sigma_{y_i}$  reduced and increased by one third, compared to the standard calibration.<sup>14</sup>

Predictably, the less reliable projections of future GDP are, the greater the potential role for intensity targets, and the greater the potential improvement from optimal indexation. With reduced GDP uncertainty, increases in expected abatement are just 5% and 8% for standard and optimal indexation respectively; while under greater GDP uncertainty, respective improvements are 14% and 27% (again compared to 10% and 17% in the standard calibration).

### *Risk aversion*

If risk aversion is stronger, the advantage of intensity targets is also greater; if parties are less averse to the risk of losses, then designing mechanisms to mitigate risk is less important also. Figure 3 shows the improvements from optimal intensity targets as function of risk aversion. The greater the degree of risk aversion, the greater the increase in expected global abatement under endogenous targets – ranging from no change to improvements over 20%. Note that expected dollar-valued gain  $G$  is greater with intensity targets even under risk neutrality, as it is a function of net uncertainty.

### *GDP–emissions linkage*

The strength of linkage between fluctuations in emissions and in economic activity determines whether and by how much GDP indexation can improve on absolute targets. In sensitivity analysis, we first assume that only half (instead of all) of energy sector emissions are linked with GDP, resulting in lower values for  $\alpha_i$  across the board. In this case, standard intensity targets overall perform worse than absolute targets, because they badly overcompensate for fluctuations in GDP (Table 6). Optimal intensity targets, at low levels of indexation, still improve the outcome compared to absolute targets. If however the overall emissions-GDP linkage is stronger than in the standard scenario (here, by assuming that half of non-energy sector emissions are linked with GDP, in addition to all of the energy sector), standard intensity targets perform very

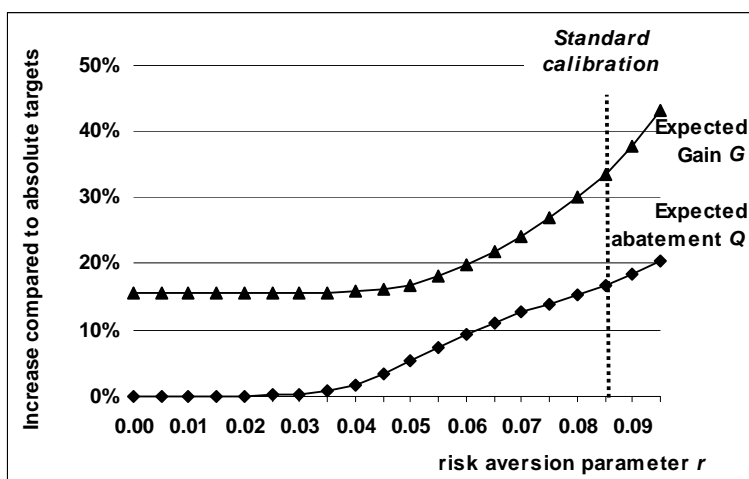
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<sup>14</sup> For comparability, the risk aversion parameter  $r$  was adjusted so that the overall impact of uncertainty in the reference case remained the same. All other parameters remained unchanged.

well. Optimal indexation then improves the outcome compared to standard intensity targets only marginally.

A post-Kyoto treaty might well exclude sources of greenhouse gas emissions that are highly variable and difficult to monitor, such as tropical deforestation; and many less developed countries, where 'linked' emissions tend to constitute a smaller share of the total, may not be in a position to take on emissions targets and take part in permit trading, due to institutional constraints. Overall, GDP and emissions covered by the treaty would then tend to be linked more closely, as fuel combustion emissions play a comparatively greater role. On the other hand, it is likely that at least some emissions sources within the energy sector are in fact largely independent of GDP (such as energy use for heating and cooling), contrary to our simplifying assumption in calibrating  $\alpha_i$ . In turn, the performance of standard intensity targets for the energy sector would not be as good as indicated in this sensitivity analysis.

**Figure 3** Sensitivity analysis on risk aversion (for optimal intensity targets)



**Table VI** Sensitivity analysis of GDP–emissions linkage

	Standard calibration	Less linkage	Greater linkage
Range of $\alpha_i$	0.18 to 0.97	0.09 to 0.485	0.59 to 0.98
<i>Increase in global abatement compared to absolute targets</i>			
Std intensity targets	10%	-15%	19%
Optimal intensity targets	17%	7%	20%

Note: Risk aversion parameter  $r$  is adjusted to preserve the Reference Case criterion of a one third reduction in abatement in the Reference Case compared to certainty equivalence.

## 6. Applicability and drawbacks of target indexation

We have presented a theoretical and empirical argument that intensity targets could yield substantial improvements compared to absolute targets, in an international greenhouse treaty. Our model describes a world where uncertainty presents a problem because of cost uncertainties within the treaty (rather than the economy as a whole), where some degree of year-by-year uncertainty about overall allowable emissions under the treaty is of no consequence, and implementation issues are ignored. Here we discuss whether relaxing these assumptions could weaken or even reverse the case for intensity targets, and discuss how applicable intensity targets might be in a real-world policy context.

### 6.1 *Pro-cyclical effects and framing of uncertainty*

Linking permit allocations with GDP can reduce uncertainty within an emissions trading treaty, but has a pro-cyclical effect that may be undesirable: In the event of an economic downturn, permit allocations would be cut back, at a time when countries may least be able to afford losing net revenue from permit trading.

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 – though a very modest one, as it turns out. From this broader perspective, intensity targets diminish a useful stabilisation effect! 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 relative magnitudes of GDP and total permit value may help explain this. The value of permits is small relative to the size of economies – in our calibration, total permit value is around 1% of global GDP – so changes in permit allocations would only



amount to a small fraction of the change in GDP that triggers them. We think the view that emissions trading could act as a stabilizer or otherwise of broader economic fluctuations, and should be designed with this in mind, will not hold sway with policymakers as long as the magnitude of financial flows under emissions trading is small relative to the economy overall.

However, the stabilization argument may be more applicable for industry level emissions targets, and where financial flows under permit trading can account for a significant share of the overall size of the operation; for example for firm-level CO<sub>2</sub> permit trading among electricity generators.

## *6.2 Shifting uncertainty to emission levels*

By allowing country's target levels to respond to realized GDP, the overall amount of emissions allowable under a treaty with intensity targets is not fixed; in other words, some uncertainty is shifted away from costs and on to emissions levels. This has been put forth as an argument against target indexation (Dudek and Golub 2003).

We have opted to set this issue aside in our modelling because in practice, variability in emissions as a result of target indexation would have a negligible effect on atmospheric concentrations of greenhouse gases, and because there is no identifiable threshold that emissions should not exceed. All that climate science can tell policymakers is that the lower greenhouse gas emissions, the better. Greenhouse gases are a stock pollutant with long decay times, and the complexity of atmospheric systems so far has precluded identification of particular threshold levels. The situation might be quite different for other pollutants.

It is also important to note that intensity targets increase uncertainty about environmental impacts only insofar as fluctuations do not cancel out between countries. For a global scheme, only a global boom would result in higher-than-expected emissions under the treaty. A much more prevalent pattern is for some countries to grow slower than expected while others grow faster, with offsetting effects on activity-indexed permit allocations overall. Further, any under- or overshooting of expected global target amounts could be compensated for if targets were periodically re-negotiated.

## *6.3 Complexity and window-dressing*

By bringing in play an additional variable for permit allocation, intensity targets create greater complexity and could reduce transparency. Monitoring, verification and

administration of the trading scheme would be 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). Further, differentiating the degree of indexation would in practice pose significant technical and political challenges: Neither determining the optimal degree of indexation, nor negotiating such differentiation between countries, will be easy.

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).

These downsides could be important, and the potential benefits from intensity targets have to be weighed carefully against them. Nevertheless, we believe that the advantages in reducing uncertainty through intensity targets may well outweigh increased complexity. Window-dressing can be dealt with by presenting intensity targets in terms of their expected emission levels, or as absolute targets with an adjustment term, as in [3.3].

#### *6.4 Intensity targets for developing countries in a post-Kyoto treaty*

Our quantitative analysis shows that intensity targets could make it more attractive for all countries to join an international climate treaty – in line with the original motivation behind proposals for target indexation, which was to encourage developing countries to participate in the Kyoto Protocol or a successor treaty (see Introduction). Would the improvements be large enough to make a difference to the participation decision by developing countries?

Increases in expected dollar-valued payoff estimated here are large, both in percentage as well as in absolute terms. However, the changes in target levels are more modest: the move from absolute to optimal intensity targets shifts South's aggregate endogenous target by 1.5 percentage points (on top of South's reduction commitment of 7.6 percentage points in the reference case), as readily seen from Table V. If all gains from lower uncertainty were used specifically to offer more lenient targets to developing countries, with commensurately tighter commitments in rich countries, the

changes would be of a similar magnitude. Flexible target design might thus be able to 'tip the balance' in particular cases where countries are nearly indifferent between taking on a given target or not, but the improvements are unlikely to be large enough to overcome more deep-seated problems of international equity, cooperation and politics.

Of the global potential gains from intensity targets, most would accrue from applying target indexation in developing countries, given that uncertainty (and probably risk aversion) is greatest there. However, the downsides and practical difficulties of target indexation are also likely to be most acute in less developed countries. So overall, intensity targets may in fact be best suited to industrializing, rather less developed countries.

## 7. Conclusions

Uncertainty about future paths of economic and emissions growth can be an important obstacle to effective emissions trading schemes, as such schemes create 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 GDP-related fluctuations in emissions. We have provided a theoretical analysis of emissions trading with endogenous intensity targets under output-linked and other uncertainties in emissions, applied it in a new multi-country empirical model of a post-Kyoto, cooperative climate treaty, 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 global climate treaty, compared to a reference scenario using absolute targets. *Standard* intensity targets, which are indexed one-to-one to GDP, can reduce overall cost uncertainty and lead to better outcomes than absolute targets, but they can systematically over- or undercompensate for GDP-related fluctuations. In four out of our 18 regions, an absolute target would be preferable to one-to-one indexation. *Optimal* intensity targets, where the degree of indexation is tailored to the extent of each country's GDP-emissions linkage and the stringency of its target commitment, always perform better than absolute targets. We have derived a simple rule for optimal target indexation.

In our model calibration of a 2020 climate treaty that covers all countries and the majority of greenhouse gases, standard and optimal intensity targets for all countries would result in a 10% and 17% increase in global abatement respectively, compared to absolute targets. Welfare improvements are larger still, and even if target levels were fixed and risk aversion played no role, optimal target indexation could increase dollar-valued gains from a climate treaty by around 20%. The extent of the potential improvements depends on how uncertain future GDP is; how strong future links between fluctuations in emissions and in GDP are; how risk-averse decisionmakers are in negotiating a treaty; and whether uncertainties are framed only in terms of the treaty, or in terms of economies as a whole.

Optimal degrees of indexation would differ strongly between countries, with 'super-indexation' 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 1.2% respectively, if their GDPs turn out 1% higher or lower than expected. For developing countries by contrast, optimal indexation would typically be only partial. Tailoring target indexation

would offer great advantages over a one-size-fits-all approach, but would require detailed country-level analysis and may be difficult to negotiate. Whether or not a continuum of target indexation – rather than just the two-way choice between absolute and standard intensity targets – is appealing and practical to treaty negotiators remains to be seen.

The degree of GDP-emissions linkage, its variation between countries, and consequently the importance of differentiated indexation also depends on which emissions sources are covered by the treaty. In further work, we plan to investigate optimal intensity targets for emissions from fossil fuel combustion only, which will necessitate more detailed empirical work on the linkage between fluctuations in GDP and energy sector emissions. Other future research may include applying the MAGES-GHG model to non-cooperative (free riding) behaviour, and assessing the effect of flexible target design on free-riding incentives; and modeling other flexible target options, such as non-binding targets or a price cap in the permit market.

Our overall policy conclusion is that intensity targets may offer a better chance of success for a future international greenhouse treaty than Kyoto-style absolute targets, but that they are certainly no magic wand. Flexible targets could help make target commitments more acceptable to developing countries, make it politically more acceptable for the United States to re-enter the process, and even help achieve more stringent climate commitments across the board. These advantages have to be weighed against increased complexity and the risk that intensity targets might be used as a means of window-dressing, making climate commitments look more stringent than they really are. Finally, while more flexible mechanism design can be useful, it will not resolve the deadlock in global climate negotiations: ultimately, 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.

## Appendix: Calibration of the MAGES-GHG model

### *Notes on calibration*

The following is in addition to description of the calibration in Section 4. The full set of parameters used in MAGES-GHG for a global climate treaty to take effect in the year 2020 is given in Table A1.

### *Emissions, GDP and population*

Data for the base year 2000 are from the World Resource Institute's CAIT database (WRI 2003), which provides a compilation of data from a range of sources. In calibrating BAU emissions  $E_i^b$  we include carbon dioxide (CO<sub>2</sub>) from the energy sector (mainly combustion), CO<sub>2</sub> from land-use change (mainly deforestation in tropical countries), and emissions of methane and nitrous oxide from a range of sources. Projected growth rates for BAU CO<sub>2</sub> emissions at 2020 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 extrapolate growth rates from 1990–2000, and for land-use change assume that annual emissions remain constant.

For GDP, we use purchasing power parity (PPP-) adjusted GDP in the year 2000 as the basis for projections, and projections from EIA and IEA. Population growth is extrapolated.

### *Marginal abatement cost (MAC) curves*

Abatement potentials  $M_i$  are calibrated for energy-derived CO<sub>2</sub> 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. For non-CO<sub>2</sub> 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<sub>2</sub> emissions.

### *Uncertainties and the GDP-emissions link*

The calibration of uncertainty parameters  $\sigma$  and the degree of GDP-emissions linkage  $\alpha_i$  is described in Section 4, and is based on empirical findings summarised in

Section 2. Sufficient data is available to differentiate emissions uncertainties between Northern and Southern countries, while we use only one common parameter for MAC uncertainty. Uncertainty about emissions in the non-linked sector ( $\sigma_{pi}$ ) differs between countries as they depend on the share of methane, nitrous oxide and CO<sub>2</sub> from land-use change in each country. A separate paper on the empirical work is in preparation and can be requested from the authors.

#### *Valuation of emissions reductions*

Parameters for valuation of, or benefit from, global abatement are not observable, so we infer them on the basis of structural indicators.

As discussed in Section 3, a political plausible calibration is achieved by setting each country's relative per-capita valuation  $V_i/L_i$  on the basis of per capita income  $Y_i/L_i$  as a proxy for ability to pay, and cumulative emissions of energy CO<sub>2</sub> from 1970 to 2000 per capita, as a proxy for historical responsibility for future climate change, with ability to pay weighted twice as heavily. Total valuation  $V$  was chosen scaling so that our reference scenario exactly *halves* future growth in global emissions. Conveniently, our valuation shares for North and South fall halfway in-between the corresponding ratios of climate change damages in two well-known estimates (Fankhauser 1995 and Tol 2002, compiled in Finus et al. forthcoming), though there are large differences for individual countries.

We did not opt 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, as poor countries have more pressing immediate concerns such as health and education (Schelling 1997).

The slope parameter  $W_i$  of the GHG marginal benefit curve is chosen to be a small and constant share of  $V_i$  ( $W_i = V_i * 0.01$ ). This results in a slight upward slope of the marginal benefit curve, in line with the well-recognised notion that due to the nature of greenhouse gases as a long-lived stock pollutant, the marginal damage curve is almost flat (Pizer 2002).

#### *Risk aversion*

See text in Section 4.

**Table A1: Parameter values in the MAGES-GHG model**

Country (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 (st.dev.) <b>a</b>	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 <sub>2</sub> equivalent)	..	G t <sup>2</sup> /yr.\$	..	..	..	..	\$/t	yr/\$	yr/\$	\$/yr
	$L_i$	$Y_i$	$E_i^b$	$\alpha_i$	$M_i$	$\sigma_{Yi}$	$\sigma_{\eta i}$	$\sigma_{\rho i}$	$\sigma_{C i}$	$V_i$	$W_i$	$r$	$z_i = 1/(Y_i/L_i)$
United States (N)	0.366	16.98	8.80	0.83	0.051	0.20	0.22	0.28	6.34	5.33	0.053	0.8617	0.022
Europe (N)	0.623	17.12	5.91	0.86	0.025			0.27		5.20	0.052		0.036
Japan (N)	0.134	4.74	1.55	0.97	0.003			0.30		1.36	0.014		0.028
Australia (N)	0.024	0.83	0.66	0.66	0.006			0.27		0.26	0.003		0.029
Canada / NZ (N)	0.042	1.52	1.17	0.61	0.007			0.25		0.48	0.005		0.028
Russia	0.195	2.77	2.85	0.91	0.031	0.25	1.49	0.015		0.070			
China	1.561	14.80	8.81	0.76	0.100	0.27	3.85	0.038		0.106			
India	1.453	7.64	3.04	0.58	0.030	0.28	1.78	0.018		0.190			
Brazil	0.225	2.40	2.57	0.23	0.021	0.30	0.57	0.006		0.094			
Argentina	0.048	0.91	0.45	0.48	0.003	0.28	0.23	0.002		0.053			
Mexico	0.136	1.77	0.84	0.74	0.006	0.27	0.46	0.005		0.077			
Korea (S.)	0.057	1.58	0.79	0.92	0.004	0.29	0.41	0.004		0.036			
Indonesia	0.276	1.42	3.45	0.18	0.033	0.30	0.34	0.003		0.194			
South-East Asia	0.264	2.31	2.21	0.43	0.018	0.29	0.56	0.006		0.114			
South Africa	0.063	1.03	0.66	0.89	0.006	0.26	0.31	0.003		0.062			
Northern Africa	0.202	1.33	0.74	0.69	0.006	0.26	0.34	0.003	0.152				
Middle East	0.322	2.12	2.41	0.66	0.021	0.24	0.63	0.006	0.152				
Rest of the World	2.160	6.74	7.12	0.32	0.057	0.28	1.89	0.019	0.320				
<i>Aggregates:</i>													
North	1.2	41.2	18.0	0.83	0.091	0.20	0.22	..	6.34	12.6	0.126	0.8617	0.029
South	7.0	46.8	35.9	0.55	0.335	0.27	0.37	..		12.9	0.129		0.149
Global	8.2	88.0	54.0	0.64	0.426	..	..	..		25.5	0.255		0.093

Europe includes Western and Eastern Europe (EU-28 countries plus Norway, Switzerland, Iceland and Balcan states; RUS: Russia, 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).

**a:** Standard deviations for emissions outside the energy sector: Methane 0.22; nitrous oxide 0.33; CO<sub>2</sub> from land-use change 0.31.  $\sigma_{\rho i}$  depends on shares of these gases in each country.



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