Optimal intensity targets for emissions trading under uncertainty

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Abstract:

Uncertainty about future economic growth and structure makes a country's costs of achieving a greenhouse gas emissions target uncertain. This can weaken the stringency of commitments under a system of tradeable emissions permits, and make it harder to bring on board developing countries if they fear economic losses; but developing country participation is crucial for a future global climate treaty to succeed.

We analyse how well intensity (GDP-indexed) targets for emissions deal with uncertainty, using a new stochastic, static, partial equilibrium model of emissions trading under uncertainty called FLUTE (Flexibility for Lower Uncertainty in Trading Emissions). It includes three uncertainties: about future economic growth, energy emissions intensity, and non-energy emissions. The degree to which intensity targets are indexed to GDP is continuous, including absolute, Kyoto-style targets as a limiting case. Countries are risk averse about their expected payoffs from global abatement and costs net of permit trading, but ignore GDP fluctuations when negotiating a treaty. Target levels and intensity degrees are jointly optimised by maximising expected global payoff, subject to an equity criterion. Our model is calibrated for a world divided into 18 important and/or illustrative countries and regions, and for a "future" in 2020. Practical challenges of intensity targets, and applications of our model to non-binding targets, and to pollutants other than greenhouse gases, are discussed.

We find that by reducing uncertainty, optimal intensity targets could achieve global abatement one seventh higher than under absolute targets, whereas standard intensity targets achieve abatement around one twelfth higher. Either improvement is useful, but no magic wand: ultimately, achieving deep cuts in emissions will be costly, and rich countries will have to pay if it is to happen. Optimal intensity targets are super-indexed to GDP for many rich countries; for example, Japan's target would optimally rise by 13% if its GDP turns out 10% higher than expected, whereas optimal target indexation for Australia and most developing countries would be below one.

For Australia, the key implication is that there are ways to improve the design of a future treaty that builds on the Kyoto Protocol. If a future Australian government were to re-engage with the Kyoto process, it could be a formidable advocate of flexible economic instruments to improve international greenhouse policy.

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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 economic uncertainties. What will the value of avoided damages be, and how much will it cost to comply with fixed emission targets? 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, 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, as well as a further watering down of commitments by those nations that ultimately ratified the treaty. Bringing developing countries on board, essential for a meaningful future global climate agreement, brings even greater challenges from economic uncertainty. Poor countries' decisionmakers can ill afford to sign onto a treaty that risks major cost blow-outs or 'stifling development'.[1]

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 emissions trading scheme represents a large scale commitment to this instrument (Kruger and Pizer 2004, Boemare and Quirion 2002), a number of US States are considering their own cap-and-trade systems (Aulisi et al. 2005), and such systems are likely to be the

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

starting point for the next round of global climate negotiations. In any case, 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.

Here we take this dominance of cap-and-trade schemes as given, for good or ill. We ask whether designing such schemes better can help 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, chief among them making targets more flexible, for example by indexing target allocations to GDP, thus making them targets for the emissions/GDP ratio or *intensity*. Target indexation has been proposed as a way for making it easier for developing countries to commit to greenhouse targets (Baumert et al. 1999, Philibert and Pershing 2001, Ellerman and Wing 2003), and featured in Argentina's greenhouse target proposed in the aftermath of the Kyoto negotiations (Bouille and Girardin 2002, Barros and Conte Grand 2002). It has received greater attention in the policy debate since the Bush administration’s voluntary (and close to business-as-usual) target for future carbon intensity of the American economy (Pew Center 2003, van Vuuren et al. 2002, Aldy 2004, Pizer 2005).

While uncertainty has been recognised as a major obstacle to cap-and-trade schemes, it has so far received little attention in the empirical literature. Most economic models of emissions trading schemes are deterministic: witness the many modeling studies on the Kyoto Protocol (Weyant 1999, Springer 2003). Uncertainty, if addressed at all, is typically dealt with by sensitivity analyses, solving the model under different assumptions about key parameters – for example for ‘low’ and ‘high’ emissions growth. This is useful but falls far short of true uncertainty analysis, because only some points from the probability distribution are selected. Similarly, studies that present multiple results using point estimates of uncertain parameters (e.g. Lecocq and Crassous 2003) usefully show the range of plausible outcomes, but can say little about optimal policy choices under uncertainty.

More systematic analysis of parameter uncertainty in non-linear deterministic models can be done by Monte Carlo methods, a technique used by Nordhaus (1994) in his seminal analysis of the optimal level of global greenhouse abatement. Pizer (2002) also averaged over a large number of random realizations to quantify the superiority of price control over quantity control for greenhouse gases. For larger models, particularly those with many regions, very many model runs are needed, which is computationally expensive. This perhaps explains why uncertainty analysis has rarely been done with the large global CGE models commonly used for economic analysis of climate policies,[2] and we know of no large-scale CGE modeling study with a systematic analysis of uncertainty in emissions trading.

Representation of uncertainty in theoretical models of emissions trading has so far been restricted to smaller, more stylised models. Stochastic elements have been introduced to the game-theoretic analysis of environmental agreements (Helm 1998, Kolstad 2004), by modeling uncertainty and learning about the environmental benefit from emission reductions. A few studies have included cost uncertainty in the theoretical modeling, including Bohm and Carlén (2002) who looked at compensation payments between risk-averse parties in emissions trading when future emissions are uncertain, and Haurie and Viguier (2003) who analysed permit markets under uncertainty about the participation of some polluters in emissions trading.

In this paper we present a stochastic, globally integrated, though mainly partial equilibrium, approach to modelling emissions trading with flexible targets under uncertainty, named FLUTE (Flexibility to Lower Uncertainty in Trading Emissions). Our model here includes three types of uncertainties affecting future emissions, and computes expectations of random variables analytically, rather than approximately by many runs of a deterministic model. We optimise the summed expectations of all countries' risk-averse payoffs from abatement benefits minus abatement and trading costs (but ignoring GDP cycles as such), and thus endogenise the target levels, in similar vein to Nordhaus and Yang (1996). Our main contributions are the theoretical and empirical construction of the FLUTE model, and also using it to derive valuable insights about which target levels and degrees of indexing optimise the outcome of emissions trading, as a guide for optimal policy. Intensity targets could be of interest wherever pollution is closely related to some level of output, and our greenhouse-based study could lead to systematic analysis of intensity targets for other pollutants. And we are already extending the model to the analysis of non-binding greenhouse targets, where some parties can withdraw from a cap-and-trade scheme without penalty.

In the empirical application, we calibrate the FLUTE model for 18 world regions, using data and projections from the literature, and empirical estimates of uncertainty parameters. We infer parameters for valuation of emissions reductions and risk aversion, so as to achieve stylised facts that we think apply, based on our reading of the international climate policy debate. Numerical solutions of the empirical model

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[2] See the studies discussed in Weyant (1999) and Springer (2003). MIT's EPPA model has been applied in repeated simulations with random realisations to assess uncertainty of long-term emissions paths (Webster et al. 2003).

indicate the magnitude of improvements in environmental effectiveness and dollar-valued payoff that could be expected from intensity targets in a global climate treaty.

We begin by laying out in Section 2 the theoretical principles of our model: uncertainties affecting future business-as-usual emissions; the definition of a flexible type of emission target with some degree of linkage to GDP, with an absolute, Kyoto-style target just being the limiting case of zero linkage; the concept of a country's (risk-adjusted) payoff from joining an emissions trading treaty; as well as discussion of the frame of reference for the payoff function and applicability of the model to other emissions trading schemes. Section 3 analyses the theoretical payoffs from a fully inclusive treaty under uncertainty, and establishes conditions for optimality. Section 4 describes how the empirical model is calibrated for a world divided into 18 regions or "countries", and computes a reference scenario with absolute targets, against which intensity targets can be compared. Section 5 gives global and country-level results for policy scenarios, where we show by how much intensity targets could improve the environmental outcome and countries' expected payoffs from a climate treaty, especially if the degree of GDP-indexation is optimised for each country. Section 6 concludes.

2. THEORY, I: UNCERTAINTIES IN EMISSIONS, INTENSITY TARGETS, AND THE CONCEPT OF PAYOFF

2.1 Main features of the theoretical model

Our FLUTE model of emissions trading (ET) under uncertainty is built around quadratic abatement costs and linear abatement benefits for each country, and can include any number of countries of any size. We assume the ET treaty is inclusive enough that abaters in all countries act as price-takers in the resulting global permit market. Our framework is partial equilibrium, in that abatement costs have no effect on gross domestic product (GDP), and (comparative) static in that though abatement commitments are made ’now’, they are acted on at just one point in the ’future’. Empirically, we choose this point to be 2020, but the theory is independent of the date, and there is no discounting because all costs are in the future. Each country’s dollar-valued (net) benefits from its abatement policy are its net financial surpluses from abatement and emissions trading (if any), plus its valuation of global abatement. These benefits are subject to risk aversion when translated into levels of "payoff". Optimised payoffs are then used to determine target levels (commitments) endogenously.

Some simplifying assumptions are necessary in order to keep the model fully analytic and intuitively understandable, while including any number of unequal countries. As usual, we ignore transactions costs; in particular, we assume all greenhouse gas emissions are included in our model, and there is costlessly monitoring and enforcement. It also means future emissions can adjust instantly to different future emission permit prices, so there is no need to decide the size and timing of irreversible investments in abatement. We linearise often in our model, but given the relatively short (10-15 year) timescale of empirical interest here, linearisation errors are acceptably small.

We now set out the FLUTE model for a set of n countries or regions indexed either by $i = 1,...,n$ or $k = 1,...,n$, and use these summation notations:

$$\Sigma_{i=1}^{n} z_i \equiv \Sigma z_i \equiv \Sigma z_k \equiv z; \quad \Sigma_{i=1}^{n-1} z_i \equiv \Sigma_{-n} z_i \equiv \Sigma_{-n} z_k \equiv z_{-n} \;;$$

$$\Sigma_{k=1,k\neq i}^{n-1} z_k \equiv \Sigma_{-i-n} z_k \equiv z_{-i-n} \;; \qquad (z_1,...,z_n) \equiv \mathbf{z}. \qquad [2.1]$$

A more general suffix used later is h, which counts from $1,...,m$. In the empirical model in Sections 4-5, $n = 18$, and in presenting some results the subscript $_N$ denotes a sum over the 5 ’Northern’ countries, while $_S$ denotes a sum over the 13 ’Southern’ countries.

2.2 Modelling uncertainties in output, intensity, and non-output-linked emissions

We first describe the effect of three separate sources of uncertainty in total emissions, denoted E t/yr where t means a tonne of CO_2-equivalent of greenhouse gases (GHGs),[1] in any economy. They are:

- uncertainty in output, measured by GDP and denoted Y \$/yr, where \$ means constant 2000 US dollars;
- uncertainty in "intensity", or emissions/GDP, E/Y t/\$, denoted η; and
- uncertainty in other, non-GDP-linked emissions.

As part of this, we specify that only some fixed share of total emissions is linked to GDP. We expect uncertainties to be much higher for some countries than for others, but our analysis is quite general, and can apply to any country. No other sources of uncertainty are included in FLUTE, so a different model may be needed if these other uncertainties are the focus of interest. For example, comparisons of price-based controls (e.g. emission taxes) with quantity-based controls (e.g. tradeable emission permits) usually follow Weitzman (1974) by focusing on uncertainties in the benefit and cost functions, which are absent here.

Formally, we assume country i's future, realised, business-as-usual (BAU) GDP is $\tilde{Y}_i$, normally distributed with expectation Y_i (a tilde always denotes a random or uncertain variable, with the variable without the tilde being the expectation of the variable) and standard deviation $\sigma_{Yi}Y_i$:

$$\tilde{Y}_i = Y_i(1+\varepsilon_{Yi}) \ \ \$/\text{yr}, \quad \varepsilon_{Yi} \sim \text{N}(0,\sigma_{Yi}), \quad Y_i,\ \sigma_{Yi} > 0 \text{ constants,} \qquad [2.2]$$

and its future, realised, BAU intensity (emissions/GDP ratio) is $\tilde{\eta}^b_i$, defined similarly:

$$\tilde{\eta}^b_i = \eta^b_i(1+\varepsilon_{\eta i}) \ \ \text{t}/\$, \quad \varepsilon_{\eta i} \sim \text{N}(0,\sigma_{\eta i}), \quad \eta^b_i,\ \sigma_{\eta i} > 0 \text{ constants,} \qquad [2.3]$$

In part of the economy, future, realised, BAU emissions are $\tilde{E}^b_{i\delta}$, jointly subject to uncertainties in GDP and intensity:

$$\tilde{E}^b_{i\delta} = \alpha_i\tilde{Y}_i\tilde{\eta}^b_i = \alpha_i Y_i(1+\varepsilon_{Yi})\eta^b_i(1+\varepsilon_{\eta i}) \ \ \text{t/yr, where:} \qquad [2.4]$$

α_i ($0 < \alpha_i < 1$) is the fixed share of the economy where emissions depend on GDP. (In fact, we will approximate α_i by the share of the energy sector in total emissions.) In the rest of the economy, denoted ρ, future BAU emissions, $\tilde{E}^b_{i\rho}$, are subject to uncertainty that is independent of GDP and intensity:

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[1] Units are shown only where they first appear or for clarification.

$$\tilde{E}^b_{i\rho} = (1-\alpha_i)Y_i\eta^b_i(1+\varepsilon_{\rho i}) \text{ t/yr}, \quad \varepsilon_{\rho i} \sim \mathrm{N}(0,\sigma_{\rho i}). \qquad [2.5]$$

The ε_{Yi}, $\varepsilon_{\eta i}$ and $\varepsilon_{\rho i}$ are all independent,[2] so the probability density function of the errors is

$$e^{-\frac{1}{2}\Sigma[(\varepsilon_{Yi}/\sigma_{Yi})^2+(\varepsilon_{\eta i}/\sigma_{\eta i})^2+(\varepsilon_{\rho i}/\sigma_{\rho i})^2]} \,/\, (2\pi)^{3n/2}\Pi^n_{i=1}(\sigma_{Yi}\sigma_{\eta i}\sigma_{\rho i}) =: \phi_{3n}(\sigma), \text{ say.} \qquad [2.6]$$

and the expectation of any random variable $\tilde{Z}$ is

$$\mathrm{E}[\tilde{Z}] := \int_{\mathbb{R}^{3n}} \tilde{Z}(\varepsilon)\, \phi_{3n}(\sigma,\varepsilon)\, d\varepsilon, \text{ where} \qquad [2.7]$$

$$\sigma := (\sigma_{Y1},\ldots,\sigma_{Yn},\sigma_{\eta 1},\ldots,\sigma_{\eta n},\sigma_{\rho 1},\ldots,\sigma_{\rho n}) \text{ and } \varepsilon := (\varepsilon_{Y1},\ldots,\varepsilon_{Yn},\varepsilon_{\eta 1},\ldots,\varepsilon_{\eta n},\varepsilon_{\rho 1},\ldots,\varepsilon_{\rho n}). \qquad [2.8]$$

Defining country *i*'s realised total BAU emissions as $\tilde{E}^b_i := \tilde{E}^b_{i\delta} + \tilde{E}^b_{i\rho}$ then means

$$\tilde{E}^b_i \quad = \alpha_i Y_i\eta^b_i(1+\varepsilon_{Yi})(1+\varepsilon_{\eta i}) + (1-\alpha_i)Y_i\eta^b_i(1+\varepsilon_{\rho i}) \text{ t/yr.} \qquad [2.9]$$

So GDP uncertainty ε_{Yi} affects emissions in part of the economy, but structural shifts and other random influences ($\varepsilon_{\eta i}$) also play a role there. In the other part of the economy, emissions are completely independent of GDP and subject to random shocks or errors ($\varepsilon_{\rho i}$). For analytical tractability we then *linearise* all the errors throughout this paper:

$$\begin{aligned} \tilde{E}^b_i &\approx \alpha_i Y_i\eta^b_i(1+\varepsilon_{Yi}+\varepsilon_{\eta i}) + (1-\alpha_i)Y_i\eta^b_i(1+\varepsilon_{\rho i}) \\ &= [1+\alpha_i(\varepsilon_{Yi}+\varepsilon_{\eta i})+(1-\alpha_i)\varepsilon_{\rho i}]E^b_i, \text{ where } E_{bi} := Y_i\eta_i^b. \qquad [2.13] \end{aligned}$$

2.3 Defining intensity targets under uncertainty

Here we define a general emissions target where the degree of GDP-indexation is a continuous variable, so our target is a continuum which includes absolute (zero-indexed) targets and intensity (positively indexed) targets. We assume the international climate treaty defines a target as:

W_i t/\$, an emission intensity target; combined with

$\beta_i \geq 0$, a pure number that is the degree to which the target is indexed to GDP, with *super-indexation* ($\beta_i > 1$) being quite possible.

The treaty rules are then that the total emission target comprises an absolute (fixed) amount $(1-\beta_i)W_iY_i$ and GDP-linked amount $W_i\beta_i\tilde{Y}_i$:

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[2] In principle, the FLUTE model can handle non-independence, but we would then also need to include theoretically, and moreover estimate empirically, a matrix of $(3n-1)(3n/2)$ covariances.

$\tilde{X}_i = (1-\beta_i)W_iY_i + W_i\beta_i\tilde{Y}_i$ t/yr is the emissions target. [2.14][3]

Since targets are most commonly quoted as proportions or percentages, it is convenient to define the proportional target here as

$x_i := W_i/\eta^b_i$, hence $W_iY_i = x_iY_i\eta^b_i = x_iE^b_i = \mathrm{E}[\tilde{X}_i] =: X_i$. [2.16]

Our general formula for a general emissions intensity target is then

$\tilde{X}_i = (1-\beta_i)x_iE^b_i + \beta_ix_iE^b_i(1+\varepsilon_{Yi}) = x_iE^b_i(1+\beta_i\varepsilon_{Yi})$, [2.17]

and two special cases are

$\beta_i = 0 \Rightarrow$ *absolute* target, $\tilde{X}_i = X_i = x_iE^b_i$, and [2.19]

$\beta_i = 1 \Rightarrow$ *standard intensity* target, $\tilde{X}_i = x_iE^b_i(1+\varepsilon_{Yi})$. [2.21]

2.4 Abatement costs, benefit and the concept of payoff

2.4.1 Emissions, abatement and abatement costs

A country's future (and hence uncertain) BAU emissions (a level at which marginal and total abatement costs are zero) are denoted $\tilde{E}^b_i$ t/yr, abatement is denoted $\tilde{Q}_i$ t/yr, and actual, abated emissions are denoted $\tilde{E}^*_i$ t/yr, so:

$\tilde{E}^*_i = \tilde{E}^b_i - \tilde{Q}_i$ t/yr. [2.28]

(Future) marginal abatement costs (MAC) are assumed linear in abatement $\tilde{Q}_i$, with slope $1/M_i$, where parameter M_i t^2/\$.yr is called *abatement potential*. Marginal and total abatement costs, denoted $\tilde{c}_i$ and $\tilde{C}_i$ respectively, are then

$\tilde{c}_i = \tilde{Q}_i/M_i$ \$/t and $\tilde{C}_i = \frac{1}{2}\tilde{c}_i\tilde{Q}_i = \frac{1}{2}\tilde{Q}_i^2/M_i$ \$/yr. [2.31]

2.4.2 Benefits of climate states, and gains from changes in state

A *state* of the world is any (future) economic equilibrium, with some condition determining (future, uncertain) emissions abatement. We consider three types of states in Section 3:

(i) *No Abatement*, so that *all* countries have BAU emissions;

(ii) some or all countries abate *Unilaterally*;

(iii) all n countries abate in accordance with their targets under an *ET treaty*.

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[3] One could have different levels of the absolute and intensity targets, with say $\tilde{X}_i = (1-\beta_i)W_{i1}Y_i + \beta_iW_{i2}\tilde{Y}_i$, instead of [2.14]. But this makes [2.17] more complicated, and remains for further work.

Unilateralism is different from No Abatement, since any country that cares about global abatement will do some abatement on its own, albeit much less than under an ET treaty.

Any state will have both financial consequences for each country − its net profit from ET, if any, minus its abatement cost, a sum we call the country's *financial surplus*, generically denoted $\tilde{F}_i$ − and environmental consequences, a generic level of global abatement $\tilde{Q}$. Financial surplus and global abatement are combined into a country's net, dollar-valued benefit of being in some state relative to No Abatement, or just *benefit* for short. We do this in a strongly linear way, meaning that (net) benefit, generically denoted $\tilde{B}_i$, is the sum of $\tilde{F}_i$ and some multiple of $\tilde{Q}$, rather than a quadratic function of $\tilde{Q}$, for reasons explained in Section 3.2:

$$\tilde{B}_i(\tilde{F}_i,\tilde{Q}) \quad := \tilde{F}_i + V_i\tilde{Q} \quad \$/\text{yr}, \qquad [2.33]$$

where the parameter

V_i (> 0) \$/t is country i's fixed level of concern about marginal global emissions abatement, which applies only to its government's, not individual abaters', decisions.

We then define country i's dollar-valued gain from any change in state as the difference in benefits between two states, say $^{(1)}$ and $^{(2)}$ (specific labels will be introduced in Section 3). Say that

$\tilde{B}_i^{(1)}$ is country i's benefit from state $^{(1)}$ (typically some kind of unilateralism), while

$\tilde{B}_i^{(2)}$ is country i's benefit from state $^{(2)}$ (typically some ET treaty).

Then the *gain* from moving state from state $^{(1)}$ to $^{(2)}$ is:

$$\tilde{G}_i \quad := \tilde{B}_i^{(2)} - \tilde{B}_i^{(1)} \quad \$/\text{yr}. \qquad [2.37]$$

Formally, the benefit of any state could then be regarded as the "gain" from a move from no abatement to that state, but such moves are of no interest for policy purposes. Like [2.33] and most other results in Section 2, [2.37] for $\tilde{G}_i$ is a generic formula, and it is not until Section 3 that tilde denotes results specific to full ET.

2.4.3 Payoff, and the cost of uncertainty

Gain as just defined is not the same as a country's payoff from a change in state. We intend payoff to be what determines a country's political decisions about climate policy action, and will add different countries' payoffs together when assessing the overall desirability of a set of targets for an ET treaty. However, the important topic of quantifying how payoff determines the probability that a country will actually join (sign up to) an ET treaty remains for further work. Payoff allows for the diminishing marginal value of dollar-valued sums, which results in risk aversion and hence an inherent cost of risk (uncertainty). We need risk aversion in order to compare different flexible target types, as will also be explained in Section 3.2, when we discuss the linear benefit function [2.33]. Specifically, we assume that per capita gain

$$\tilde{g}_i \quad := \tilde{G}_i/L_i \quad \text{\$/yr.person,} \qquad [2.38]$$

where L_i is country i's future population, gives a generic *per capita payoff* for each person in the country of

$$\tilde{u}_i := u_i(\tilde{g}_i) := \tilde{g}_i + (1-\mathrm{e}^{-r\tilde{G}_i})/Y_i \quad \text{\$/yr.person.} \qquad [2.39]$$

Here Y_i is country i's expected real, future, total GDP from [2.2]. Parameter r (> 0) yr/\$, the coefficient of absolute risk aversion, is intended to be a globally constant parameter reflecting the psychology of an average human being, independently of the population, emissions intensity or per capita GDP of the country they live in.

Corresponding to this, a country's *total payoff* from a change in state is generically defined as

$$\tilde{U}_i := U_i(\tilde{G}_i) \quad := L_i u_i(\tilde{g}_i) \qquad [2.41]$$

$$= \tilde{G}_i + (1-\mathrm{e}^{-r\tilde{G}_i})/y_i \quad \text{\$/yr, where } y_i := Y_i/L_i \text{ \$/yr.person.} \qquad [2.42].$$

The exponential function in [2.39] and [2.42] is chosen largely for theoretical tractability, but the $1/y_i$ factor in [2.42] is empirically motivated, to match the stylised fact that uncertainty matters more in poor (low y_i) countries.

From the definition of payoff functions in [2.39] and [2.42], and the expectation function in [2.7], country i's *per capita expected payoff* and *total expected payoff* from gain $\tilde{G}_i$ are respectively

$$\mathrm{E}[\tilde{u}_i] = \int_{\mathbb{R}^{3n}} [\tilde{g}_i + (1-\mathrm{e}^{-r\tilde{G}_i})/Y_i]\ \phi_{3n}(\sigma)\ d\varepsilon, \text{ and} \qquad [2.44]$$

$$\mathrm{E}[\tilde{U}_i] = \int_{\mathbb{R}^{3n}} [\tilde{G}_i + (1-\mathrm{e}^{-r\tilde{G}_i})/y_i]\ \phi_{3n}(\sigma)\ d\varepsilon, \qquad [2.46]$$

and we can define

the *fixed-target per capita cost of uncertainty for country i*:

$$\psi_i := u_i(\mathrm{E}[\tilde{g}_i]) - \mathrm{E}[u_i(\tilde{g}_i)], \quad \text{and} \qquad [2.47]$$

the *fixed-target total cost of uncertainty for country i*

$$\Psi_i := U_i(\mathrm{E}[\tilde{G}_i]) - \mathrm{E}[U_i(\tilde{G}_i)]. \qquad [2.48]^4$$

Another caveat is that defining payoff for a change of benefit as in [2.37] while using a strictly concave $u_i(.)$ in [2.39] may create framing effects, where the ranking of expected payoffs of two states $^{(1)}$ and $^{(2)}$ depends on which state they are compared to, e.g.

$$\mathrm{E}[u_i(\tilde{b}_i^{(2)}-\tilde{b}_i^{(1)})] > \mathrm{E}[u_i(\tilde{b}_i^{(3)}-\tilde{b}_i^{(1)})] \quad \textit{but} \quad \mathrm{E}[u_i(\tilde{b}_i^{(2)})] < \mathrm{E}[u(\tilde{b}_i^{(3)})]. \qquad [2.52]$$

In the limit $r \to \infty$ we have infinite loss aversion, while in the limit $r \to 0$ we have a purely linear payoff function which eliminates all framing effects.

2.5 Criteria for equity and participation in ET treaties, and endogenous emission targets for a reference scenario

In an ET treaty among n countries, any number of target levels are possible. To provide a uniform basis for assessing different types of targets, we therefore need a reference scenario, including some kind of rule for how targets are to be differentiated between countries. There are many proposed rules for, and subsequent analyses of, target differentiation or "burden sharing" (see for example Baer et al. 2000, den Elzen et al. 1999, Babiker and Eckaus 2002, Baumert et al. 2003, Berk and den Elzen 2001 and Rose et al. 1998). However, most of these rules depend directly on properties other than their costs and benefits of implementation, and so are *exogenous* to the kind of ET model used. Moreover, none take account of the degree of uncertainty that countries are exposed to.

Here, we determine emission targets for our reference scenario *endogenously*, that is, dependent on their costs and benefits of implementation in our model, which automatically includes the cost of uncertainty. Specifically, we define a reference scenario where global payoff is maximized, subject to rules on how that payoff is distributed. Both the overall level of abatement and the differentiation of

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[4] The "fixed-target" qualification is needed here because both formulae implicitly assume the same set $\mathbf{x} = \{x_1,...,x_n\}$ of target levels in each term. Yet we assume next (Section 2.5) that target levels are endogenous, being chosen to optimise global payoff subject to a constraint. So for all empirical results reported, the target levels behind the uncertain cases (absolute, standard intensity and intensity target types) and the certain case all differ. So [2.47] and [2.48] are not the exact formulae actually used for reporting costs of uncertainty.

commitments (country targets $\{x_i\}$) are then endogenous and differ according to target design, parameters and any other changes. Under a target type that eliminates some of the uncertainty, payoff is greater and thus leads to more abatement in the optimum by way of tighter targets.

To find a set of endogenous targets for our reference scenario, we solve the model as a *cooperative* game, subject to three conditions:

(i) for simplicity, all targets are absolute (so all $\beta_i = 0$ as in [2.19]) and binding in type;

(ii) total payoff is distributed among participating countries so that their expected payoffs *per capita* are all equal (our *equity* criterion) and positive (our *participation* criterion). This restricts the available sets of targets to the *equal share space* := $\{\mathbf{x} \text{ s.t. } E[\tilde{u}_i(\mathbf{x})] = E[\tilde{u}_k(\mathbf{x})] > 0 \text{ for all } i,k\}$; [2.59]

(iii) expected global payoff $\Sigma E[\tilde{U}_i(\mathbf{x})] = \Sigma L_i E[\tilde{u}_i(\mathbf{x})]$ is maximised. [2.61]

However, in sensitivity analysis in Section 5, we will find that the exact choice of equity criterion in [2.59] makes little difference when comparing the relative merits of absolute and intensity targets. This is despite the fact that a different criterion such as equalising payoff per $ of GDP would lead to quite different target levels, obviously giving relatively more lenient targets to rich countries and more stringent targets to poor ones.

In assuming above that global payoff is maximised, we obviously set aside the analysis of climate treaties as *non-cooperative* games (Carraro and Siniscalco 1993, Barrett 1994), and instead assume that political factors can bring about cooperation in multilateral negotiations (Eckersley 2004), so that the free-riding problem can be dealt with politically. The "equal share criterion" within [2.59] is our equity rule, achieved solely through differentiation of targets; there are no cash transfers. Similar approaches were taken by Chander and Tulkens (1997), Böhringer and Helm (2001) and Germain and Steenberghe (2003). Once participation and equity rules are determined, the assumption in [2.61] that expected global payoff will be maximised follows naturally, as negotiators are assumed not to "leave money on the table at the conclusion of their negotiations" (Barrett 2003).

2.6 The importance of framing effects when defining payoff

Above we have assumed that the payoff a country perceives from joining an ET treaty in the face of uncertainty about emissions is framed as a function of just the financial and environmental consequences of joining the treaty. This may seem logical from the point of view of the negotatiors, 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 at the same time? As an obvious example of this broader frame of reference, could not payoff be defined as a function of the uncertain gain from treaty accession *plus* the uncertain GDP itself, so that we evaluate $U(\tilde{G}_i+\tilde{Y}_i)$ instead of $U(\tilde{G}_i)$?

Which frame of reference to use for negotiation is a matter for political and psychological choice, but the choice profoundly affects how flexible targets are assessed. 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, and so will be perceived as less desirable than absolute targets. So they will be preferred to absolute targets only if the frame of reference ignores the effect of GDP variation on national welfare. 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, and tend not to take the broader, economy-wide perspective. We accept this conventional framework, and assess how climate treaties cope with uncertainties in isolation from the rest of the economy. We refer again to the broader frame of reference only when presenting empirical results and concluding.

2.7 Possible applications to other pollutants

All our assumptions have now been given, except that emissions trading among countries will be assumed to make all their marginal abatement costs $\tilde{c}_i$ equal the global price $\tilde{p}$ of a tradeable permit. So it is a good point to explore how well the FLUTE model might apply to pollutants other than GHGs, especially to the more common case where pollutants cause a one-way rather than mutual externality (say for simplicity that none of the polluting parties i are affected), and the parties are firms not countries, so GDP would no longer be the relevant measure of their outputs.

That the externality affects only non-parties to the ET treaty would formally make all valuation parameters V_i zero, which means benefit in [2.33] is just financial surplus. It also means that targets cannot be set endogenously, as the parties would cooperatively all choose zero abatement if maximising global payoff in [2.61]. So the pollution control authority would have to set global abatement Q exogenously, in the light of valuations of pollution damage that occurs to parties other than those in the ET treaty.

That the polluting parties are firms rather than countries makes a bigger difference. Populations L_i would disappear from the model, so the payoff definition in [2.42] would need to be modified, perhaps measuring payoff as a share of firm output rather than per capita. How firms perceive the cost of uncertainty in an ET scheme, and what would be a sensible equity criterion for the authority to impose, would nevertheless repay further thought. Less obviously but more importantly, many firms would not treat their own future expected output Y_i as a parameter separate from their abatement choices, mainly because of salience and control. For the targets we envisage as politically plausible for 2020, GHG abatement costs turn out to be a tiny proportion of GDP, and GDP is anyway hard to control. But for many firms and pollutants (for example electricity generators and sulphur dioxide emissions), abatement costs can be significant relative to output revenues, so that future output and abatement would then be chosen jointly. So insofar as output-linked uncertainties in emissions define the FLUTE model, it could be applied to firm-level pollutants only where likely abatement costs are small enough for abatement to be decided independently of output; yet still large enough for uncertainty in abatement costs to be cause for concern. Which pollutants at ET schemes would fit this double requirement remains for further investigation.

3. THEORY, II: PAYOFFS FROM ET UNDER UNCERTAINTY

Here we calculate formulae for the payoffs the countries make from joining an ET treaty with emissions targets with a continuous degree of intensity. Even with the number of "countries" into which we divide the world in our empirical analysis being only $n = 18$, there are a huge number of possible combinations of countries that could join or not join an ET treaty. For simplicity, we consider only two *states* of climate policy:

(i) *Full ET*: all n countries join an ET treaty, and thus have tradeable emission targets as defined by [2.14]; and

(ii) *Unilateralism*: no ET treaty, and all countries abate unilaterally.[5]

In Sections 3.1.1-2 we compute the financial surpluses, abatements and benefits that result from each of these states. In Section 3.2 we use results from Sections 3.1.1 and 3.1.2 to compute the gains, payoffs and expected payoffs from the change of state from GU to Full ET.

3.1 Benefits and abatements

3.1.1 Full ET

Let the common realised permit price at which Full ET occurs in future be $\tilde{p}$ \$/t.[6] To maximise its financial surplus, every country i chooses its abatement $\tilde{Q}_i$ to equate its marginal abatement cost to the permit price:

$$\tilde{c}_i = \tilde{p}, \qquad [3.1]$$

hence from [2.31] abatement equals price times abatement potential:

$$\tilde{Q}_i = \tilde{p}M_i \text{ for all } i, \text{ and from [2.1], } \tilde{Q} = \tilde{p}M. \qquad [3.2]$$

Country i's financial surplus from Full ET, denoted as $\tilde{F}_i$, is its (emissions) permit sales revenue minus its abatement cost:

$$\tilde{F}_i := \tilde{p}\tilde{S}_i - \tilde{C}_i, \text{ where } \tilde{S}_i := \tilde{X}_i - \tilde{E}^*_i, \qquad [3.3]$$

i.e. permit sales quantity is target emissions minus abated emissions.

Given perfect enforcement, global abated emissions equals global emission targets:

$$\Sigma\tilde{E}^*_i = \Sigma\tilde{X}_i, \text{ hence from [2.28], } \tilde{Q} = \Sigma\tilde{E}^b_i - \Sigma\tilde{X}_i. \qquad [3.7]$$

Taking expectations of this and using [2.18] and [2.24] then gives:

$$Q := \mathrm{E}[\tilde{Q}] = \Sigma E^b_i - \Sigma x_i E^b_i = \Sigma(1-x_i)E^b_i > 0. \qquad [3.8]$$

Using this and [3.2] gives the expected permit price p as total expected BAU emissions ΣE^b_i minus total expected target emissions $\Sigma x_i E^b_i$, all divided by total abatement potential M:

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[5] We could therefore call this "Global Unilateralism", to distinguish it from the situation where only some countries abating unilaterally; but the latter is not analysed here, though the theory could readily include it.

[6] So far a tilde ($\tilde{\ }$) has denoted generic uncertainty in any realised future. But from now on it denotes realised uncertainty *in the state of Full ET*, and we will use different notations to denote realised uncertainty in other states.

$p = \mathrm{E}[\tilde{Q}/M] = \Sigma(1-x_i)E^b_i/M > 0.$ [3.9]

To get $\tilde{p}$ in terms of the errors $\{\varepsilon_{Yi},\varepsilon_{\eta i},\varepsilon_{\rho i}\}$ in [2.8], first define

$\Omega_i := \ 1 - \beta_i x_i/\alpha_i$ [3.11]

as the proportion of GDP-linked emissions uncertainty ε_{Yi} *not* neutralised by the intensity component $\beta_i x_i$ of *i*'s target. We then define country *i*'s *net emissions uncertainty*, after allowing for the uncertainty neutralised by intensity targets, as:

$\tilde{T}_i \ := [\alpha_i(\Omega_i\varepsilon_{Yi}+\varepsilon_{\eta i})+(1-\alpha_i)\varepsilon_{\rho i}]\ E^b_i;$ whence [3.12]

$\tilde{T} := \Sigma\ [\alpha_i(\Omega_i\varepsilon_{Yi}+\varepsilon_{\eta i})+(1-\alpha_i)\varepsilon_{\rho i}]\ E^b_i$ [3.13]

is the global net emissions uncertainty; and also by [2.1]

$\tilde{T}_{-i} \ := \Sigma_{-i}\ [\alpha_k(\Omega_k\varepsilon_{Yk}+\varepsilon_{\eta k})+(1-\alpha_k)\varepsilon_{\rho k}]\ E^b_k,$ and [3.14]

$\tilde{T}_{-i-n} \ := \Sigma_{-i-n}[\alpha_k(\Omega_k\varepsilon_{Yk}+\varepsilon_{\eta k})+(1-\alpha_k)\varepsilon_{\rho k}]\ E^b_k.$ [3.16]

Note that all *T*-variables have zero expectation, e.g. $\mathrm{E}[\tilde{T}_{-i}] = 0$.

Then starting with the difference between total BAU emissions $\Sigma\tilde{E}^b_i$ and total realised targets $\Sigma\tilde{X}_i$, routine algebra *[see Referees' Appendix 1]* shows that total realised abatement:

$\tilde{Q} = pM + \tilde{T}$, to first order. [3.17]

So from this and [3.2], the realised permit price and its square are

$\tilde{p} = p + \tilde{T}/M$ and $\widetilde{p^2} = p^2 + 2p\tilde{T}/M$, to first order. [3.18]

Starting with [2.33] and [3.3], further lengthy but routine algebra *[see Referees' Appendix 2]* then yields the following key result for a Full ET equilibrium, to first order in ε terms:

dollar-valued benefit compared to No Abatement

$\tilde{B}_i \ := \tilde{p}\tilde{S}_i - \tilde{C}_i + V_i\tilde{Q}$ [3.23]

$= B_i - p\tilde{T}_i + H_i\tilde{T}$ [3.24]

$= B_i - (p-H_i)\tilde{T}_i + H_i\tilde{T}_{-i}$ \$/yr, [3.25]

where we define

$B_i(\mathbf{x}) := \tfrac{1}{2}p^2M_i - p(1-x_i)E^b_i + V_i pM$ \$/yr, and [3.26]

$H_i(\mathbf{x}) := [pM_i-(1-x_i)E^b_i]/M + V_i$ \$/t. [3.27]

It is then straightforward to show *[see Referees' Appendix 3]* that expected global benefit $B = \Sigma B_i$ is maximised by choosing targets $\{x_i\}$ such that the expected permit price $p = \Sigma V_i = V$, which of course is the Samuelson (1954) principle of optimal pricing for a public good. However, this is not the same as maximising expected global payoff, which we investigate below.

3.1.2 Unilateralism

We denote this case by a hat and tilde $\hat{\tilde{}}$, or just a hat $\hat{}$ for quantities which are certain. From [2.33] and [2.31], country *i*'s net benefit is then:

$$\hat{\tilde{B}}_i = -\,\hat{\tilde{C}}_i + V_i\hat{\tilde{Q}} = -\tfrac{1}{2}\hat{\tilde{Q}}_i^2/M_i + V_i(\hat{\tilde{Q}}_{-i}+\hat{\tilde{Q}}_i). \qquad [3.33]$$

Individually optimal abatement $\hat{\tilde{Q}}_i$ is chosen to maximise $\hat{\tilde{B}}_i$ on the assumption that $\partial\hat{\tilde{Q}}/\partial\hat{\tilde{Q}}_i = 1$, so $-\hat{\tilde{Q}}_i/M_i + V_i = 0$, hence

$$\hat{\tilde{Q}}_i = \hat{Q}_i := V_iM_i \ \text{ and } \ \hat{\tilde{Q}} = \hat{Q} = \Sigma V_kM_k, \qquad [3.34]$$

so that maximised Unilateral benefits for a typical country are then

$$\hat{\tilde{B}}_i = \hat{B}_i := -\tfrac{1}{2}V_i^2M_i^2/M_i + V_i(\Sigma V_kM_k) = \tfrac{1}{2}V_i^2M_i + V_i(\Sigma_{-i}V_kM_k). \qquad [3.38]$$

So in our model, a country's Unilateral abatement and abatement cost are certain, because they depend only on its (certain) marginal valuation and its (certain) abatement potential; and global abatement and each country's benefit are likewise certain.

3.2 Expected gains, payoffs and increased global abatement

Combining [2.37] with [3.25] and [3.38], the (future) gain to any country *i* from a move from Unilateralism to all countries joining (now, and enacting in future) a Full ET treaty is

$$\tilde{G}_i \quad = G_i - (p-H_i)\tilde{T}_i + H_i\tilde{T}_{-i}, \ \text{ where} \qquad [3.63]$$

$$G_i \quad := B_i - \tfrac{1}{2}V_i^2M_i - V_i(\Sigma_{-i}V_kM_k), \qquad [3.64]$$

so from [2.42], a country's payoff from the move is

$$\tilde{U}_i \quad = G_i - (p-H_i)\tilde{T}_i + H_i\tilde{T}_{-i} + (1-\mathrm{e}^{-r[G_i\,-\,(p-H_i)\tilde{T}_i\,+\,H_i\tilde{T}_{-i}]})/y_i. \qquad [3.66]$$

From [3.66] and [2.46], *any country i's expected payoff from Full ET compared to Unilateralism* can be shown (see Appendix 1) to be

$$U_i := \mathrm{E}[\tilde{U}_i] = G_i + (1-\mathrm{e}^{\frac{1}{2}r^2\Gamma_i^2-rG_i})/y_i, \ \text{ where} \qquad [3.67]$$

$$\Gamma_i^2 := H_i^2\Sigma_{-i}D_k^2 + (p-H_i)^2D_i^2, \ \text{ and} \qquad [3.68]$$

$$D_i^2 := E^{b\,2}_i[(\alpha_i\Omega_i\sigma_{Yi})^2+(\alpha_i\sigma_{\eta i})^2+(1-\alpha_i)^2\sigma_{\rho i}{}^2]. \qquad [3.69]$$

From [2.48], [2.42] and [3.68], country *i*'s total fixed-target cost of uncertainty is then

$$\Psi_i = e^{-rG_i}\,(e^{\frac{1}{2}r^2\Gamma_i^2}-1)/y_i. \qquad [3.71]$$

How then can targets be chosen to maximise any country's expected payoff (or minimise their cost of uncertainty)? The only choice variables above lie in $\Omega_i = 1 - \beta_i x_i/\alpha_i$, and from [3.67]-[3.69], U_i is maximised when all Ω_i's are set to zero. From [3.11], this immediately yields an important result:

Proposition 1: A country's expected payoff is maximised when

$\beta_k x_k = \alpha_k$ for all k, which we call *optimal intensity targets.* [3.72]

Intuitively, any country's expected payoff is highest when *all* countries have target levels x_k and degrees of intensity β_k set to exactly neutralise the GDP component of their own emissions uncertainties. If target levels have been determined beforehand by some institutional agreement, then [3.72] can be seen as a rule for setting all intensity degrees at

$$\beta_k = \beta_k^* := \alpha_k/x_k. \qquad [3.73]$$

However, since optimality under intensity targets here entails choosing the x_k's and β_k's jointly to maximised global expected payoff [2.61], [3.72] is a better way of stating the optimality condition. One striking aspect of [3.72], which holds true for many countries, is worth stating as:

Corollary 1: If a country's optimal target is tighter than its share of GDP-linked emissions ($x_k < \alpha_k$), then its optimal intensity target is super-indexed to GDP ($\beta_k > 1$).

In order to use the equal share criterion [2.59] under uncertainty and thus compute endogenous targets, we also need expected per capita payoff. From [2.39] this can readily be shown *[see Referees' Appendix 4]* to be

$$E[\tilde{u}_i] = g_i + (1-e^{\frac{1}{2}r^2\Gamma_i^2-rG_i})/Y_i = E[\tilde{U}_i]\,/\,L_i, \qquad [3.77]$$

while from [3.71]/L_i, country *i*'s per capita fixed-target uncertainty cost is

$$\psi_i = e^{-rG_i}\,(e^{\frac{1}{2}r^2\Gamma_i^2}-1)/Y_i \qquad [3.78]$$

Per capita versions of other expected total payoff results below can be readily obtained by the same method, and will not be given explicitly here.

Finally, from [3.2] and [3.34] the increases in realised country and global *abatement* resulting from ET occurring rather than Unilateralism are

$$\Delta\tilde{Q}_i := \tilde{Q}_i - \hat{\tilde{Q}}_i = (\tilde{p}-V_i)M_i \text{ and } \Delta\tilde{Q} := \tilde{Q} - \hat{\tilde{Q}} = \tilde{p}M - \Sigma V_i M_i. \qquad [3.79]$$

Expected changes in abatement are the same expressions without the tildes:

$$\Delta Q_i := Q_i - \hat{Q}_i = (p-V_i)M_i \text{ and } \Delta Q := Q - \hat{Q} = pM - \Sigma V_i M_i. \qquad [3.81]$$

However, the empirical results actually cited will be total abatements Q_i and Q, since these are more readily related to target percentages widely discussed in the policy literature.

3.3 Justifying a linear benefit function

Having set out all our theory, we can at last return to explain a key modelling choice in FLUTE made at the start. Despite the cost function in [2.31] being quadratic in country-level abatement $\tilde{Q}_i$, our benefit function in [2.33] is linear in global abatement $\tilde{Q}$, yet we use a non-linear payoff function in [2.39]. Why? First, because if risk aversion r in [2.39] is zero, payoff and gain are identical. But from [3.67], the reward from Full ET (rather than Unilateralism) would then be measured as just the expected gain, G_i. Now from [3.64], [3.21] and [3.9],

$$G_i = \tfrac{1}{2}[\Sigma(1-x_k)E^b_k/M]^2 M_i - [\Sigma(1-x_k)E^b_k/M](1-x_i)E^b_i + V_i\Sigma(1-x_k)E^b_k$$
$$- \tfrac{1}{2}V_i^2 M_i - V_i(\Sigma_{-i}V_k M_k), \qquad [3.82]$$

so β_i, the intensity degree of i's target (the key focus of interest in this paper), has no effect on G_i. So a zero r would not show any kind of advantage of intensity ($\beta_i > 0$) over absolute ($\beta_i = 0$) targets. As for the (net) benefit function, it might seem both symmetric, and consistent with the long-established Weitzman (1974) approach, to use a function quadratic in abatement $\tilde{Q}$ (hence allowing varying slopes of marginal benefit against $\tilde{Q}$). However, because we have omitted any uncertainty in the functional form of the benefit function, it can readily be shown *[see Referees' Appendix 5]* that β_i would still have no effect on the expected gain from ET. So a quadratic benefit function would increase theoretical complexity and moreover double the number of country parameters to be inferred empirically, while saying nothing about the advantages of target flexibility, which would still require a payoff function like [2.39]. Hence our chosen modelling approach.

4. IMPLEMENTATION AS AN EMPIRICAL SIMULATION MODEL

The FLUTE model is implemented as an empirical simulation model in the GAMS package.[7] Here we summarise the calibration methods and data used (further details are in Appendix 2), and outline the reference case against which policy scenarios are compared and the main sensitivities of the numerical modeling.

4.1 Calibration and results reported

FLUTE is calibrated for the year 2020, 'the future'. We have chosen to divide the world into 18 regions or countries, just known as 'countries', ranging in economic size from Argentina and Australia to the USA and Europe. 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 and China, and allows detailed analysis for selected developing countries such as Mexico and South Africa.

Parameters for (future) business-as-usual emissions ($E^b{}_i$), abatement potential (M_i), GDP (Y_i) and population (L_i) are calibrated to recent data, projections and estimates from the literature. We include emissions and abatement from all major greenhouse gas sources.

Based on new empirical research (summarised in Appendix 2), we estimate that uncertainties about future emissions intensity in the energy sector $\{\sigma_{\eta i}\}$ are definitely greater than about future GDP $\{\sigma_{Yi}\}$, that uncertainties about future non-energy emissions $\{\sigma_{\rho i}\}$ are somewhat greater than about energy emissions intensity $\{\sigma_{\eta i}\}$, and that uncertainties are greater in the South than in the North. We also find that the share of emissions linked with GDP is roughly the share of the energy sector in total emissions, so we set the GDP-linked emissions shares as $\alpha_i = E^b{}_{energy\_i} / E^b{}_i$, using an obvious notation.

Parameters for the valuation of emissions reductions $\{V_i\}$ and for risk aversion r are inferred from observations about the international climate policy debate. A more comprehensive approach might be a survey of expert opinion in each country along the lines of Weitzman (2001), but that remains for further work. Instead, per capita valuations $\{V_i/L_i\}$ are assumed to be a function of per capita income and historical responsibility for greenhouse emissions, and cross-checked with climate change damage estimates from the literature. Risk aversion is calibrated so that it results in

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[7] Generalised Algebraic Modeling System (Brooke et al. 1998), using the CONOPT nonlinear programming solver algorithm (Drud 1992).

significantly less stringent commitments under uncertainty, but without stifling agreement altogether. Our aim is to capture the essential features of the global climate policy debate and broad differences between countries.

Below we report the results for selected variables in the model. The key point of comparison between the simulations is the expected amount of global abatement Q [3.8], which shows the environmental effectiveness of a climate treaty. We interpret the percentage change in Q between scenarios as a measure of the performance of different target designs under uncertainty. Related to this measure is the target reduction in emissions compared to BAU, $1–x_i$ (from [2.16]), for individual countries or regional groups. A further important variable used for comparison used is the dollar-valued measure for global payoff, U from summing [3.67]. Note that U is defined over the difference between the treaty and Unilateral abatement, whereas Q is the difference between the treaty and BAU (No Abatement). This choice keeps reported abatement consistent with targets x_i, which [2.17] defines in relation to BAU emissions. It would be simple to subtract global Unilateral abatement using [3.34], especially since this is constant and given below.

4.2 Reference scenario

As defined in [2.59] and [2.61], the absolute emission targets used for the reference scenario are chosen to maximise expected global payoff from a full ET treaty subject to per capita payoff being equalised across all countries. The differentiation of commitments between countries is thus taken to be the outcome of a cooperative game.[8] 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 emissions in the reference scenario (E^*) grow by 16% from 2000 to 2020, compared to a projected increase of 32% (E^b) under business-as-usual (BAU). This is equivalent to a reduction of 12% below BAU, as shown in Table 4.1. The expected amount of abatement undertaken under the treaty is 6.5 Gt/yr, compared to combined abatement in the unilateral case $\hat{Q}$ from [3.34] of just under 1 Gt/yr. The expected permit price p from [3.9], 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 (Pearce et al. 1996). Global payoff from

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[8] This is in contrast to conventional analyses of burden sharing under a climate treaty where targets are determined outside of the model (for example Babiker and Eckaus 2002; Baumert et al. 2003; Berk and den Elzen 2001; Rose et al. 1998).

the climate treaty, U, is around 73 billion \$/yr, compared to the Unilateral situation – keeping in mind however that the absolute magnitude of payoff depends on our assumptions about valuation and risk aversion.

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, by choice of an appropriate value for the risk aversion parameter r; and payoff is then 22% lower. The former impact of uncertainty on the overall effectiveness of an ET treaty will serve as the key comparison for flexible target options.

Table 4.1: Reference scenario: Global results and comparison with certainty equivalence

	Reference scenario: Treaty with absolute targets under uncertainty	Treaty under certainty equivalence
Expected values of:		
Change in emissions compared to BAU ($E^*/E^b - 1$) (or target reduction as share of BAU, $x - 1$)	–12%	–18%
Change in emissions compared to emissions in year 2000 ($E^*/E_{2000} - 1$)	16%	8%
Permit price p (\$/t)	15.34	23.00
Global abatement Q (Gt/yr)	6.53	9.79
Global payoff U (G\$/yr)	72.7	93.1
Loss in global abatement due to uncertainty	33.3%	-
Loss in global payoff due to uncertainty	21.9%	-

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, greater per capita income in developed countries, reflected in high valuation of global abatement, is the decisive factor, leading to more stringent targets for Northern than for Southern countries on the whole (Table 4.2).

Targets can also be expressed as a proportion of base year emissions, here the year 2000. This shows that all developing countries 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 United States and

Europe are the largest permit buyers; China, India and the Rest of the World region are the largest permit sellers. Total valuation of global abatement (*V*) is evenly split between North and South (Appendix 2), implying much greater per capita valuation in the North. Under the equal per capita payoff rule, the North shoulders all of the financial cost (the area under the marginal cost curves) of global abatement action (50 G$/yr), while revenue from permit sales covers all of the South's aggregate abatement costs. The expected global financial cost, *F* from summing [3.3], of abatement is well below 0.1% of global GDP.

The main sensitivities for the reference case scenario are assumptions about the valuation of global emission reductions, equity constraints under cooperation, the degree of risk aversion, and coverage of emissions sources. If the North cares more about global abatement, targets are stricter for rich countries and more generous for poor countries. Similarly, different equity rules – for example, distributing overall payoff in line with each country's GDP rather than population, which might more adequately reflect political bargaining power – can shift the balance of commitments between countries. Greater risk aversion leads to a greater impact of uncertainty, and hence lower equilibrium abatement. Finally, recall that we assume that all emissions sources in all countries are covered and that there are no transaction costs, a very optimistic assumption in a world of institutional constraints (Victor 2001).

Table 4.2 Reference scenario: Targets, abatement and trading

	Target reduction 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)
Region	x_i-1	$x_i * E^b_i / E_{i2000} - 1$	$(x_i-1)E^b_i$	Q_i	$Q_i+(x_i-1)E^b_i$
North	-23%	-9%	-4.11	1.40	-2.72
South	-7%	31%	-2.41	5.13	2.72
Global	-12%	16%	-6.53	6.53	0.00

5. THE PERFORMANCE OF INTENSITY TARGETS

Intensity targets can reduce uncertainty in the permit market, as they make countries' permit allocations move with GDP, and so neutralise some of the GDP-related uncertainty. With uncertainty lower, payoff is greater, leading to tighter targets and more abatement in the optimum. We model two types of intensity targets:

- *standard intensity targets* with one-to-one indexation for all countries i, characterized by $\beta_i = 1$ in [2.14];
- *optimal intensity targets*, where $\beta_i x_i = \alpha_i$ for all i and hence uncertainty due to fluctuations in GDP is fully neutralised, as noted in [3.72].

We run scenarios with constrained global payoff maximization as in [2.59] and [2.61], and compare the results to those under the reference scenario with absolute targets.

5.1 Global results for intensity targets

With standard intensity targets, expected global abatement increases from 6.5 to 7.0 Gt/yr under absolute targets, a 7.8% increase (Table 5.1). The improvement of 0.5 Gt/yr in global abatement is about the same as current, total emissions from Korea, Mexico or Australia. Expressed differently, standard intensity targets close 15% of the gap between equilibrium abatements under certainty equivalence (9.8 Gt/yr), and under absolute targets with uncertainty. Payoff from the treaty is also increased, but by proportionally less than abatement. At the same time as this more stringent environmental outcome is achieved, the payoff from the treaty is also increased, by around 4 G$/yr – an increase of 5.5% compared to a treaty with absolute targets.

Standard intensity targets are suboptimal as they will on average over- or undercompensate for fluctuations in GDP, and under optimal intensity targets, much bigger improvements are possible than under one-to-one indexation (Table 5.1). Expected global abatement is 7.42 Gt/yr, 14% greater than under absolute targets, implying that the optimal intensity targets bridge 28% of the gap between abatement of 6.53 Gt/yr in the absolute target scenario and 9.8 Gt/yr under certainty equivalence

Table 5.1 Absolute, standard intensity and optimal intensity targets: Global results

	Absolute targets (all β_i=0)	Standard intensity targets (all β_i =1)	Optimal intensity targets (all $\beta_i = \alpha_i/x_i$)
Expected values of:			
Global abatement Q (Gt/yr)	6.53	7.04	7.42
Improvement in abatement, compared to absolute targets	-	7.8%	13.7%
Effect of uncertainty eliminated, compared to absolute targets	-	15.5%	27.5%
Global payoff U (G$/yr)	72.7	76.7	80.2

(from Table 4.1). The expected payoff under optimal intensity targets is increased by 7.5 billion \$/yr, or around 10%. These results indicate that intensity targets have the potential for large overall improvements in the payoff from a global climate treaty.

5.2 Intensity targets by country

The degree to which intensity targets can help address uncertainty, and consequently make tighter targets possible, differs greatly between countries. Intensity targets bring the greatest advantage where the share of emissions linked is with GDP (α_i) is large, uncertainty about future GDP (σ_{Yi}) is large relative to uncertainty in emissions intensity ($\sigma_{\eta i}$), and the degree of uncertainty about emissions not linked with GDP ($\sigma_{\rho i}$) is low. The increase in stringency of targets varies greatly between countries, in part depending on how stringent the reduction commitment is in the standard scenario (Table 5.2). Relative to BAU emissions, the increase in stringency varies between zero and 2.5% under standard intensity targets, and between 1% and 3% for optimal intensity targets.

By how much the stringency of commitments can increase under intensity targets also depends on how much countries risk losses in the reference scenario. They risk more if the target is tight, and if risk aversion is high. For example, China has above-average per capita costs of uncertainty in the reference scenario, but a more lenient target so as to achieve equal per capita payoff. Using intensity targets to relieve some of the uncertainty thus makes a much more stringent target for China possible. Overall, the potential for intensity targets to increase the stringency of commitments is greater in developing countries.

The optimal degree of indexation $\beta_i^* = \alpha_i / x_i$ varies greatly between countries. For most developing countries the optimum intensity target would mean sub-indexation ($\beta_i^* < 1$), owing to a relatively large share of emissions not being linked with GDP, and comparatively lenient targets. In cases where β_i^* is very low, for example Indonesia, optimally indexed intensity targets would perform much better than standard intensity targets.

The optimal indexation for Australia would be 0.81, implying that Australia's target would optimally rise by 8.1% if its GDP turns out 10% higher than expected, and fall by 8.1% if GDP turned out 10% lower than expected. This is based on the assumption that two thirds of Australia's greenhouse emissions are linked with GDP – a smaller share than in almost all other developed countries because of the importance of emissions from land-use change and agriculture in Australia. Detailed country-level empirical analysis of the nexus between fluctuations in GDP and fluctuations in emissions could no doubt improve on this estimate by determining GDP-emissions linkage at a more disaggregated level, and consequently yield a different result for β_i*. Under the assumptions made about risk aversion, valuation and equitable sharing of payoff from a climate treaty, Australia's commitment implied in its target would be 7% more stringent if all countries had optimal intensity targets, compared to absolute targets.

In several other countries, our Corollary 1 applies: the constrained-optimal target x_i is lower than the share of emissions linked with GDP (α_i), so super-indexation of its intensity target is optimal ($\beta_i* > 1$), a fact not yet recognised in the literature. Under a reasonably ambitious treaty, this is likely to happen in many advanced economies, with Japan’s super-indexation of 31% being the highest case. The difference between optimal and standard intensity targets is of course least for countries where β_i* is closest to 1, but even where $\beta_i* = 1$ there is still a difference, intuitively because from [3.18] and [3.13], better target design in all countries reduces price uncertainty in the global permit market. And the overcompensation that can happen with a standard intensity target can be so great that it performs worse than an absolute target, as happens for the Rest Of the World in Table 5.2.

Table 5.2 Intensity targets by country

	Increase in the stringency of commitment compared to absolute targets ($(x_i^{\beta>0}-1)/(x_i^{\beta=0}-1)-1$)		Degree of indexation β_i^*	Target x_i	Share of emissions linked with GDP α_i
Country (N = North)	Standard intensity targets (β_i =1)	Optimal intensity targets ($\beta_i^* = \alpha_i/x_i$)			
United States (N)	4.7%	5.6%	1.07	0.77	0.83
Europe (N)	2.7%	4.6%	1.18	0.73	0.86
Japan (N)	2.4%	4.0%	1.31	0.74	0.97
Australia (N)	4.1%	7.0%	0.81	0.82	0.66
Canada / NZ (N)	3.7%	6.2%	0.74	0.83	0.61
Russia	5.2%	8.0%	1.18	0.77	0.91
China	24.0%	29.8%	0.88	0.87	0.76
India	[a]	[a]	0.59	0.99	0.58
Brazil	7.1%	13.1%	0.25	0.91	0.23
Argentina	5.1%	8.3%	0.58	0.83	0.48
Mexico	6.3%	9.8%	0.88	0.84	0.74
Korea (S.)	3.6%	6.0%	1.12	0.82	0.92
Indonesia	2.0%	19.6%	0.19	0.94	0.18
South-East Asia	10.7%	17.3%	0.47	0.91	0.43
South Africa	4.7%	8.2%	1.09	0.82	0.89
Northern Africa	20.0%	32.0%	0.74	0.93	0.69
Middle East	11.0%	19.2%	0.72	0.91	0.66
ROW	–5.0%	42.5%	0.31	1.02	0.32
Averages:					
North	3.6%	5.1%	-	0.76	0.84
South	15.2%	28.5%	-	0.91	0.55
Global	7.8%	13.7%	-	0.86	0.64

a: India has a permit allocations above BAU ('hot air') under absolute targets, and allocations below BAU under intensity targets, so percentage comparisons are not applicable.

Regional aggregation: See Table A2.1.

5.3 Sensitivity analysis

Here we test the sensitivity of they key results to changes in the magnitude of uncertainty about GDP relative to other uncertainties, the degree to which emissions move with GDP, the degree of risk aversion, and the equity criterion.

Together, these three sensitivity analyses show that it is an empirical question just how well intensity targets can perform in reducing uncertainty, thus highlighting the need for country-level empirical research in fine-tuning the design of flexible targets. However, the core conclusions about the performance and design of intensity targets are independent of parameter variations, and the broad magnitudes of results are robust to changes in the calibration.

5.3.1 Uncertainty about GDP

From [3.69], the size of uncertainties about future GDP σ_{Yi} directly affects the performance of intensity targets compared to absolute targets. To show the impact of GDP uncertainties, we show alternative results with all σ_{Yi}'s a third lower and 50% higher than in the standard calibration (Table 5.3). As expected, the increased global abatement achieved by intensity targets changes significantly. The less reliable projections of future GDP are, the greater the potential role for intensity targets.

Table 5.3 Sensitivity analysis of GDP uncertainty

	Standard calibration	GDP uncertainty one third lower	GDP uncertainty 50% higher
	σ_{YN}=0.15 σ_{YS}=0.23	σ_{YN}=0.10 σ_{YS}=0.153	σ_{YN}=0.225 σ_{YS}=0.345
Increase in global abatement compared to absolute targets			
Std intensity targets	8%	4%	13%
Optimal intensity targets	14%	6%	30%

5.3.2 GDP–emissions linkage

If emissions are independent of economy-wide output ($\alpha_i = 0$), then linking permit allocations to GDP by using intensity targets is counterproductive. Conversely, if all emissions on average move in line with GDP, except for fluctuations in emissions intensity ($\alpha_i = 1$), then a great degree of uncertainty can be mitigated.

We first assume that only half (instead of all) of energy sector emissions are linked with GDP, resulting in lower values for α_i across the board. In this case, standard intensity targets perform worse than absolute targets, because they badly overcompensate for fluctuations in GDP (Table 5.4). Optimal intensity targets provide low levels of indexation and improve the outcome by a small degree 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 well. Optimal indexation can only marginally improve the outcome compared to standard intensity targets, but also perform significantly better than under standard assumptions.

Table 5.4 Sensitivity analysis of GDP–emissions linkage

	Standard calibration	Less linkage	Greater linkage
Range of α_i	0.18 to 0.97	0.09 to 0.485	0.59 to 0.98
Increase in global abatement compared to absolute targets			
Std intensity targets	8%	-9%	18%
Optimal intensity targets	14%	3%	19%

5.3.3 Risk aversion

If risk aversion is stronger, the advantage of intensity targets on the outcome of an emissions trading treaty is greater also; if parties are less averse to the risk of losses, then risk mitigating mechanism design is less important also. This is shown for sensitivity analysis with significantly greater and smaller risk aversion parameter r (Table 5.5). The performance of standard intensity targets changes only marginally with the degree of risk aversion, and the increase in abatement under optimal intensity targets also remains in the same broad magnitude.

Table 5.5 Sensitivity analysis of risk aversion

	Standard calibration	Weaker risk aversion	Stronger risk aversion
Risk aversion parameter	r=0.097	r=0.0755	r=0.131
Reduction in abatement compared to certainty equiv.	33%	20%	50%
Increase in global abatement compared to absolute targets			
Standard intensity targets	8%	6%	7%
Optimal intensity targets	14%	10%	18%

5.3.4 Equity criteria

We confirm here the statement in Section 2.5 that our choice of equal per capita payoff as our standard equity criterion makes little difference to the relative assessment of different types (but not levels) of targets. For example, changing to a criterion of equal payoff per $ of GDP results in very little differentiation in target levels x_i among countries, in stark contrast to our standard scenario. But under equal payoff per $, the increase in global abatement from either standard intensity or optimal intensity rather than absolute targets is only 2 percentage points less than under equal payoff per capita. Global payoff from the treaty is however slightly lower, as the poorer and more risk averse parties receive a smaller share of the overall benefit, resulting in greater overall cost of uncertainty.

5.4 Some potential drawbacks of intensity targets

As noted in Section 2.6, the frame of reference is crucial in our whole analysis. Linking permit allocations with GDP can reduce uncertainty within an emissions trading treaty, but has a pro-cyclical effect on the economy in aggregate, and would thus be undesirable from the broader perspective of overall economic stabilization.

The relative magnitudes of GDP and total permit value explain why we chose to ignore this broader perspective. The value of permits is small relative to the size of economies, and changes in permit allocations would only amount to a small fraction of the change in GDP that triggers them. In our calibration, the total value of permits is just below 1% of global GDP, and is below 2% of GDP for 17 out of our 18 countries and regions. The pro-cyclical effect of intensity targets would be in the same order of magnitude – a decrease in GDP by $100 billion would result in a decrease in the value of a country's permit allocation of, say, $1 billion. So 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 while the magnitude of financial flows under emissions trading is small relative to the economy overall.

If there was to be a much more stringent treaty with much higher permit prices and total permit value, this could of course change, but abatement commitments of such magnitude appear unlikely. However, the stabilization argument may be more applicable for schemes that apply at the industry level, 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_2 permit trading among electricity generators.

A further potential drawback of intensity targets is that monitoring and verification may be more complicated, as ex-post GDP (or some other activity variable) is used to determine permit allocations. Further, optimal intensity targets would pose significant technical and political challenges: Neither determining what the optimal degree of indexation should be, nor negotiating such differentiation between countries will be easy.

Finally, intensity targets create uncertainty about the amount of emissions allowed, if fluctuations in economic activity do not cancel out between countries. However, fluctuations in global economic growth tend to even out in the long term, and short-term divergences from the targeted amount do not matter much for long-lived stock pollutants such as greenhouse gases.

6. CONCLUSIONS

Uncertainty about future paths of economic and emissions growth can be an important obstacle to effective emissions trading schemes. Flexible target types, including intensity targets where permit allocations are linked to realised GDP, could usefully reduce the uncertainty in the permit market. We have provided a theoretical analysis of greenhouse emissions trading with general, continuously-defined intensity targets under output-linked uncertainties in emissions, and applied it in an empirical model of a climate treaty for the whole world, divided into 18 countries and regions. The target level for each country was determined by maximising the global, expected, risk-adjusted payoff of all countries joining a climate treaty, subject to the equity criterion that per capita expected payoffs are the same for all countries, and assuming that countries' frame of reference extends only to the immediate costs and benefits of the treaty, not to GDP uncertainty itself.

We have shown how, under which conditions, and by how much such intensity targets could reduce the ‘costs of uncertainty’ – the difference, caused by countries’ risk aversion, between global expected payoff of an uncertain future in 2020, and the global payoff of the equivalent certain future – and thus improve both the overall outcome and environmental stringency of a global climate treaty, compared to a reference scenario using absolute targets. A more detailed finding is that *standard* intensity targets, which are fully indexed to future, uncertain GDP, do not perform nearly as well as *optimal* intensity targets, which are indexed by the proportion of a country’s emissions linked to GDP divided by the overall target level as a proportion. Standard intensity targets can overcompensate for fluctuations in GDP, and may even end up performing worse than absolute targets, while optimal intensity targets avoid under- or overcompensating for fluctuations in GDP. We estimate that optimal intensity targets could reduce the effect of uncertainty on total abatement achievable under a global climate treaty by more than 25%, rather than about 15% under standard intensity targets. In our calibration, this translates to an increase in global abatement of 14% and 8% respectively, which is in the same order of magnitude as Australia's total emissions.

It is also important to note that, to achieve the more than 25% result, optimal intensity targets are mostly ‘super-indexed’ for rich countries. This happens because advanced economic development typically entails both a high proportion of emissions linked to GDP, and low endogenous target levels as determined by our equity criterion. For example, we find that Japan’s and Europe’s emissions targets would optimally rise by about 13% and 12% respectively, if their GDPs turn out 10% higher than expected. Whether or not such a continuum of target types – far more than just the two-way choice between absolute and standard intensity targets – is appealing and practical to treaty negotiators remains to be seen, as do the many other limitations on how well our model assumptions work in practice. Estimation and negotiation of parameters for optimal intensity targets could be a formidable task.

Further work already in hand applies our model to the idea of non-binding targets (whether absolute or intensity) for a few countries, and to the case of flexible (intensity or non-binding) targets for a single country joining an existing ET treaty. An important extension might also be to use our model to study the effectiveness of price caps (Pizer 2002) in reducing uncertainty in cap-and-trade schemes – under a price cap, permit buyers are protected against the permit price exceeding some threshold level. Finally, our overall approach to uncertainty analysis is not restricted to international greenhouse gas applications. It could well be applied to domestic greenhouse emissions trading, and to cap-and-trade schemes for other pollutants, provided abatement costs are large and uncertain enough to generate significant risk aversion, yet small enough to be decided independently of output.

The key policy conclusion from our research is that flexible emissions targets, including intensity targets, offer a better chance to bring developing countries on board an international greenhouse treaty, and to achieve more stringent climate commitments across the board. However, better mechanism design is no magic wand: ultimately, economic restructuring to achieve deep cuts in greenhouse emissions will be costly, and rich countries will have to pay if it is to happen. The political standoff between the United States, key developing countries and the European Union over climate policy needs to be resolved if there is to be a meaningful global climate treaty.

Australian policymakers may want to take note and further explore these options for improving the design of a future climate treaty that uses the cap-and-trade approach. A future Australian government might lessen its alignment with the US climate policy and engage with the European Union and Japan in their efforts to build on the Kyoto Protocol. In this case, Australia could act as a champion of flexible economic instruments to improve the effectiveness and efficiency of international greenhouse policy, a role it has played in the past.

Appendix 1 A country's expected payoff from Full ET rather than Unilateralism

To calculate country i's total expected payoff, we need to compute

$$\mathrm{E}[\tilde{U}_i] = \int_{\mathbb{R}^{3n}} [\tilde{G}_i + (1-\mathrm{e}^{-r\tilde{G}_i})/y_i]\ \phi_{3n}(\sigma)\ d\varepsilon \qquad \text{from [2.46]}$$

where from [3.63], [3.14] and [3.12]

$$\begin{aligned}\tilde{G}_i \quad &\approx G_i + H_i\Sigma_{-i}[\alpha_k(\Omega_k\varepsilon_{Yk}+\varepsilon_{\eta k})+(1-\alpha_k)\varepsilon_{\rho k}]E^b{}_k \\ &\qquad - (p-H_i)[\alpha_i(\Omega_i\varepsilon_{Yi}+\varepsilon_{\eta i})+(1-\alpha_i)\varepsilon_{\rho i}]E^b{}_i. \qquad \text{[A.1]}\end{aligned}$$

We do this by using the converse of Theorem 7 in Rohatgi and Ehsanes Saleh (2001, p.249), which is effectively that

$$\begin{aligned}&\int_{\mathbb{R}^m} \mathrm{d}\varepsilon^{(m)}\ [\mathrm{e}^{-\frac{1}{2}\Sigma_{h=1}^{m}(\varepsilon_h/\sigma_h)^2} / (2\pi)^{m/2}\Pi_{j=1}^{m}\sigma_h]\ f(Z+\Sigma_{j=1}^{m}\mu_h\varepsilon_h) \\ &\quad = \int_{\mathbb{R}} d\tau\ [\mathrm{e}^{-\frac{1}{2}(\tau/\sigma_\mu)^2} / (2\pi)^{\frac{1}{2}}\sigma_\mu]\ f(Z+\tau), \qquad \text{[A.2]}\end{aligned}$$

where, with $h = 1,...m$ while i or $k = 1,...,n$ as in [2.1],

$$\sigma_\mu{}^2 := \Sigma_h\mu_h{}^2\sigma_h{}^2. \qquad \text{[A.3]}$$

Re-inserting [2.6] into [2.46], we have $m = 3n$, $f(Z+\tau) = Z+\tau + (1-\mathrm{e}^{-r(Z+\tau)})/y_i$, $\varepsilon_1 = \varepsilon_{Y1}$, $\varepsilon_2 = \varepsilon_{\eta 1}$, $\varepsilon_3 = \varepsilon_{\rho 1}$, $\varepsilon_4 = \varepsilon_{Y2}$, ..., $\varepsilon_m = \varepsilon_{\rho n}$, and similar for $\sigma_1,...,\sigma_m$. So from [A.1] and [A.2], the constant $Z = G_i$, and the μ_h coefficients are

$$\begin{aligned}&\mu_1 = H_i\alpha_1\Omega_1E^b{}_1,\ \ \mu_2 = H_i\alpha_1E^b{}_1,\ \ \mu_3 = H_i(1-\alpha_1)E^b{}_1;\ .....\\ &\mu_{3i-2} = -(p-H_i)\alpha_i\Omega_iE^b{}_i,\ \ \mu_{3i-1} = -(p-H_i)\alpha_iE^b{}_i,\ \ \mu_{3i} = -(p-H_i)(1-\alpha_i)E^b{}_i;\ .....\\ &\mu_{m-2} = H_i\alpha_n\Omega_nE^b{}_n,\ \ \mu_{m-1} = H_i\alpha_nE^b{}_n,\ \ \mu_m = H_i(1-\alpha_n)E^b{}_n.\end{aligned}$$

$$\begin{aligned}\text{So } \sigma_\mu{}^2 &= (H_iE^b{}_1)^2[(\alpha_1\Omega_1\sigma_{Y1})^2 + (\alpha_1\sigma_{\eta 1})^2 + (1-\alpha_1)^2\sigma_{\rho 1}{}^2] + ...\\ &\quad + [(p-H_i)E^b{}_i]^2[(\alpha_i\Omega_i\sigma_{Yi})^2 + (\alpha_i\sigma_{\eta i})^2 + (1-\alpha_i)^2\sigma_{\rho i}{}^2] + ...\\ &\quad + (H_iE^b{}_n)^2[(\alpha_n\Omega_n\sigma_{Yn})^2 + (\alpha_n\sigma_{\eta n})^2 + (1-\alpha_n)^2\sigma_{\rho n}{}^2]\\ &= H_i^2\Sigma_{-i}D_k^2 + (p-H_i)^2D_i^2 \ \text{ by [3.69]}, \ = \Gamma_i^2 \ \text{ by [3.68].}\end{aligned}$$

Combining the above results then gives:

$$\mathrm{E}[\tilde{U}_i] \ = \int_{-\infty}^{\infty} d\tau\ [\mathrm{e}^{-\frac{1}{2}(\tau/\Gamma_i)^2}/(2\pi)^{\frac{1}{2}}\Gamma_i]\ [G_i+\tau+(1-\mathrm{e}^{-r(G_i+\tau)})/y_i]. \qquad \text{[A.4]}$$

Hence using the standard integrals $\int_{-\infty}^{\infty}[\mathrm{e}^{-\frac{1}{2}\tau^2/\sigma^2}/(2\pi)^{\frac{1}{2}}\sigma]\ d\tau = 1$, $\int_{-\infty}^{\infty}[\mathrm{e}^{-\frac{1}{2}\tau^2/\sigma^2}/(2\pi)^{\frac{1}{2}}\sigma]\ \tau\ d\tau = 0$, and $\int_{-\infty}^{\infty}[\mathrm{e}^{-(\frac{1}{2}\tau^2/\sigma^2+\xi\tau)}/(2\pi)^{\frac{1}{2}}\sigma]\ d\tau = \mathrm{e}^{\frac{1}{2}\xi^2\sigma^2}$,

$$\mathrm{E}[\tilde{U}_i] = G_i + (1-\mathrm{e}^{\frac{1}{2}r^2\Gamma_i^2-rG_i})/y_i, \qquad \text{which is [3.67].}$$

Appendix 2: Calibration of the FLUTE model

Table A2.1 below gives the calibration data we used for the empirical application of the FLUTE model to the 18 "countries" into which we divide the world. It also gives detailed sublists of countries, and groupings into North and South (the latter including Russia). We now summarise the data sources and methods we used for this calibration; full details are in Jotzo (2005b).

A2.1 Emissions, GDP and population

Data for emissions, output and population in the base year 2000 are from the WRI (2003) CAIT database. In calibrating BAU emissions $E^b{}_i$ we include carbon dioxide (CO_2) from the energy sector (mainly combustion), CO_2 from land-use change (mainly deforestation in tropical countries), and emissions of the remaining two main GHGs, methane and nitrous oxide, from a range of sources.

Projected growth rates for BAU CO_2 emissions at 2020 from the energy sector are taken from projections in EIA (2004, reference case projections) and IEA (2004). For non-energy GHG emissions, no consistent, regionally disaggregated projections exist. We assume that emissions of methane and nitrous oxide continue to grow at the same rate as from 1990–2000, and for land-use change, that annual emissions from deforestation remain constant everywhere.

For GDP, we use purchasing power parity (PPP-) adjusted GDP in the year 2000 as the basis for projections, as PPP is generally used for long run comparisons of income levels across countries (Taylor and Taylor 2004). For CO_2 emissions from the energy sector, GDP data for 2020 is constructed using projections from EIA and IEA. Projections of BAU emissions intensity come from dividing projections of BAU emissions by those of GDP. For population, we apply historical growth rates.

Note that in our calibration, Southern countries show more rapid emissions growth, and account for two thirds of global BAU emissions in 2020. The energy sector accounts for almost two thirds of projected emissions globally, and is relatively more important in developed (Northern) countries. Projected emissions growth is much greater for the energy sector than for other emissions sources, in line with historical trends. Projected per capita income on average is five times higher in that in Southern countries, with a larger difference if evaluated at exchange rates.

Table A2.1: Parameter values in the FLUTE model, standard calibration

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 (standard deviation)	Valuation	Risk aversion (curvature of payoff function)
	billion	trillion US$2000/yr	Gt/yr (in CO_2 equivalent)	..	G t^2/yr.$	..	..	..	$/t	yr/$
	L_i	Y_i	E^b_i	α_i	M_i	σ_{Yi}	$\sigma_{\eta i}$	σ_{pi}	V_i	r
United States (N)	0.366	16.98	8.80	0.83	0.051	0.15	0.26	0.34	4.8	0.97
Europe (N)	0.623	17.12	5.91	0.86	0.025			0.32	4.7	
Japan (N)	0.134	4.74	1.55	0.97	0.003			0.34	1.2	
Australia (N)	0.024	0.83	0.66	0.66	0.006			0.30	0.2	
Canada / NZ (N)	0.042	1.52	1.17	0.61	0.007			0.31	0.4	
Russia	0.195	2.77	2.85	0.91	0.031	0.23	0.30	0.31	1.3	
China	1.561	14.80	8.81	0.76	0.100			0.31	3.5	
India	1.453	7.64	3.04	0.58	0.030			0.32	1.6	
Brazil	0.225	2.40	2.57	0.23	0.021			0.38	0.5	
Argentina	0.048	0.91	0.45	0.48	0.003			0.33	0.2	
Mexico	0.136	1.77	0.84	0.74	0.006			0.34	0.4	
Korea (S.)	0.057	1.58	0.79	0.92	0.004			0.32	0.4	
Indonesia	0.276	1.42	3.45	0.18	0.033			0.40	0.3	
South-East Asia	0.264	2.31	2.21	0.43	0.018			0.38	0.5	
South Africa	0.063	1.03	0.66	0.89	0.006			0.31	0.3	
Northern Africa	0.202	1.33	0.74	0.69	0.006			0.30	0.3	
Middle East	0.322	2.12	2.41	0.66	0.021			0.29	0.6	
ROW	2.160	6.74	7.12	0.32	0.057			0.34	1.7	
Regional aggregates										
North	1.2	41.2	18.0	0.84	0.09	0.15	0.26	..	11.4	0.97
South	7.0	46.8	35.9	0.55	0.33	0.23	0.30	..	11.6	
Global	8.2	88.0	54.0	0.64	0.43	..	..	..	23.0	

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; ROW includes all other countries (including much of Africa, South America and South Asia).

A2.2 Marginal abatement cost curves

Abatement potentials M_i, which measure how much abatement in t/yr is achieved per marginal cost of 1 \$/t in each country, are calibrated for energy-derived CO_2 on the basis of structural characteristics of each country. The relationship between abatement potential, emissions intensity of electricity production, and the overall emissions intensity of the economy, is estimated from computable general equilibrium models of the world economy (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. Little is known about abatement costs from sources other than fossil fuel combustion (Reilly et al. 1999), so we apply one set of literature-based MAC estimates for methane, nitrous oxide and avoided deforestation to all countries. Summing over all sectors and gases yields M_i for each country.

China, Russia and India have the largest relative abatement potential (M_i/Y_i), reflecting their low energy efficiency and abundance of carbon-intensive fuels, while the smallest are in Japan and Brazil, which have very high efficiency and use of non-carbon energy respectively. Non-energy sectors account for around 45% of global abatement potential M, reflecting cheap abatement opportunities there, if institutional hurdles can be overcome.

A2.3 Uncertainties and the GDP-emissions link

Uncertainties about emissions, emissions intensity and GDP, along with the link between GDP and emissions, are central to our model. We calibrate them using new empirical research in Jotzo (2005a), who developed and applied statistical forecasting models to historical time-series data, to produce country-by-country 'forecasting errors' over 15-year time spans. These forecasting errors were aggregated to form two probability distributions, one each for OECD countries and non-OECD countries. The results were then compared to past projections by leading forecasters (EIA 1995, IEA 1995). Jotzo concluded that σ_{Yi}, $\sigma_{\eta i}$ and $\sigma_{\rho i}$, the respective uncertainties in GDP, energy-sector intensity, and non-energy emissions, are significant, even in the short term and using the best available projection tools; that all $\sigma_{Yi} < \sigma_{\eta i} < \sigma_{\rho i}$; and that σ_{Yi} and $\sigma_{\eta i}$ are greater in non-OECD than in OECD countries, while $\sigma_{\rho i}$ are similar in both groups. The resulting data are shown in Table A2.1.

Further empirical analysis of the link between fluctuations in GDP and in emissions shows that there is a strong positive correlation between fluctuations in emissions in the energy sector and fluctuations in GDP, with significant variability around the mean. For the 20 largest emitting countries, the estimated ‘elasticity of fluctuations in energy sector emissions with regard to fluctuations in GDP’ from 1971-2000 varied from 0.4 to 1.6, with a median and mean of around 1, and a statistically highly significant correlation in 19 out of 20 countries. No such clear correlation could be found for emissions outside the energy sector, as expected, since non-energy emissions are from activities such as livestock growing, deforestation and some industrial processes which do not necessarily move with GDP.

These findings are used to calibrate α_i, the share of total emissions linked with GDP in the model. We assume that emissions in the energy sector are on average linked one-to-one with GDP, yet allow for fluctuations in emissions intensity η_i; that non-energy emissions are not linked with GDP; and hence that $\alpha_i = E^b_{energy\ i} / E^b_i$.

A2.4 Valuation of emissions reductions

Valuation parameters V_i \$/t, effectively countries' willingnesses to pay for global abatement, are the key drivers of endogenous target differentiation among countries. But V_i parameters are not observable, so we infer them on the basis of structural indicators, in a way that achieves the stylised facts that we think apply.

Climate change damages have been used as a proxy for valuation of global abatement (see for example Nordhaus and Yang 1996). However, damage estimates at the regional level are highly speculative, and small differences in social discount rates translate to large differences in valuation because of the long time frames involved. 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 developing countries have more pressing immediate concerns such as health and education (Schelling 1997).

Instead, we found by trial and error that a political plausible calibration was to set each country's relative per-capita valuation V_i/L_i on the basis of both y_i, seen as its ability to pay, and cumulative emissions of energy CO_2 from 1970 to 2000 per capita, seen as its historical responsibility for future climate change, with ability to pay weighted twice as heavily. The absolute figures were then found by scaling them all so that our reference scenario exactly *halves* future growth in global emissions (i.e. an increase of 16% from 2000 to 2020 under the treaty, compared to the BAU projection of 32%). The resulting V_i figures are as shown in Table A2.1, with valuations per capita being of course much higher in Northern, industrialized countries. 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) .

A2.5 Risk aversion

The risk aversion parameter r gives the curvature of all payoff functions, and hence the impact of uncertainty on the outcome of a climate treaty. Here it is an unobserved and hence inferred parameter: we choose r so that our reference scenario with endogenous absolute targets under uncertainty achieves only *two-thirds* of the global abatement achieved by the same scenario with no uncertainty. We further expect that risk aversion plays a greater role in poorer (low Y_i/L_i) countries, where negative economic impacts would be felt more acutely. This explains the $1/y_i$ factor in the payoff function [2.42].

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Referees’ Appendix 1: Derivation of [3.17]

Starting from [3.7], the working is

$\tilde{Q} = \Sigma\tilde{E}^b{}_i - \Sigma\tilde{X}_i$, which from [2.13] and [2.17]

$\approx \Sigma[1+\alpha_i(\varepsilon_{Yi}+\varepsilon_{\eta i})+(1-\alpha_i)\varepsilon_{\rho i}]E^b{}_i - \Sigma(1+\beta_i\varepsilon_{Yi})x_iE^b{}_i$

$= \Sigma E^b{}_i - \Sigma x_iE^b{}_i + \Sigma[\alpha_i(\varepsilon_{Yi}+\varepsilon_{\eta i})+(1-\alpha_i)\varepsilon_{\rho i}]E^b{}_i - \Sigma\beta_i\varepsilon_{Yi}x_iE^b{}_i$, which from [3.8]

$= Q + \Sigma\ [(\alpha_i-\beta_ix_i)\varepsilon_{Yi}+\alpha_i\varepsilon_{\eta i}+(1-\alpha_i)\varepsilon_{\rho i}]\ E^b{}_i$, which from [3.9] and [3.11]

$= pM + \Sigma\ [\alpha_i(\Omega_i\varepsilon_{Yi}+\varepsilon_{\eta i})+(1-\alpha_i)\varepsilon_{\rho i}]\ E^b{}_i$, which from [3.13]

$= pM + \tilde{T}$ as in [3.17].

Referees’ Appendix 2: Realised net benefit from Full ET

Realised variables under Full ET are as follows. From [3.3], permit sales quantity

$\tilde{S}_i = \tilde{X}_i - \tilde{E}^*{}_i$, which by [2.28] and [3.2]

$= \tilde{X}_i - \tilde{E}^b{}_i + \tilde{p}M_i$. [R2.1]

From [3.23], realised dollar-valued benefit compared to No Abatement

$\tilde{B}_i = \tilde{p}\tilde{S}_i - \tilde{C}_i + V_i\tilde{Q}$, which from [R2.1], [2.31] and [3.2]

$= \tilde{p}\tilde{X}_i - \tilde{p}\tilde{E}^b{}_i + \tilde{p}^2M_i - ½(\tilde{p}M_i)^2/M_i + V_i\tilde{p}M$

$= \tilde{p}(\tilde{X}_i-\tilde{E}^b{}_i) + ½\tilde{p}^2M_i + \tilde{p}V_iM$, which from [3.18]

$\approx ½(p^2+2p\tilde{T}/M)M_i + (p+\tilde{T}/M)V_iM + (p+\tilde{T}/M)(\tilde{X}_i-\tilde{E}^b{}_i)$

$= ½p^2M_i + V_ipM + (pM_i/M+V_i)\tilde{T} - (p+\tilde{T}/M)(\tilde{E}^b{}_i-\tilde{X}_i)$. [R2.2]

Now from [2.17] and [2.13],

$\tilde{E}^b{}_i-\tilde{X}_i = [1+\alpha_i(\varepsilon_{Yi}+\varepsilon_{\eta i})+(1-\alpha_i)\varepsilon_{\rho i}]E^b{}_i - x_iE^b{}_i(1+\beta_i\varepsilon_{Yi})$

$= (1-x_i)E^b{}_i + [(\alpha_i-\beta_ix_i)\varepsilon_{Yi}+\alpha_i\varepsilon_{\eta i}+(1-\alpha_i)\varepsilon_{\rho i}]E^b{}_i$, which from [3.11]

$$= (1-x_i)E^b_i + [\alpha_i\Omega_i\varepsilon_{Yi}+\alpha_i\varepsilon_{\eta i}+(1-\alpha_i)\varepsilon_{\rho i}]E^b_i,$$ which from definition [3.12]

$$= (1-x_i)E^b_i + \tilde{T}_i. \qquad \text{[R2.3]}$$

Inserting [R2.3] into [R2.2] and ignoring 2nd order terms then gives

$$\tilde{B}_i = \tfrac{1}{2}p^2M_i + V_ipM + (pM_i/M+V_i)\tilde{T} - (p+\tilde{T}/M)[(1-x_i)E^b_i+\tilde{T}_i]$$

$$= \tfrac{1}{2}p^2M_i - p(1-x_i)E^b_i + V_ipM + (pM_i/M+V_i)\tilde{T} - p\tilde{T}_i - (\tilde{T}/M)(1-x_i)E^b_i$$

$$= \tfrac{1}{2}p^2M_i - p(1-x_i)E^b_i + V_ipM - p\tilde{T}_i + [pM_i/M-(1-x_i)E^b_i/M+V_i]\tilde{T}$$

which from definitions [3.26] and [3.27]

$$= B_i - p\tilde{T}_i + H_i\tilde{T},$$ which is [3.24].

Referees' Appendix 3: Optimal permit price under Full ET

From [3.24] and [3.26], global realised benefit is

$$\tilde{B} := \Sigma\tilde{B}_i = \Sigma\{\tfrac{1}{2}p^2M_i - p(1-x_i)E^b_i + V_ipM\} - p\tilde{T} + H\tilde{T}, \qquad \text{[R3.1]}$$

which using [3.9], and hence $H := \Sigma H_i = p - Q/M + V = V$, gives

$$\tilde{B} = \tfrac{1}{2}p^2M - p^2M + VpM + (V-p)\tilde{T}. \qquad \text{[R3.2]}$$

Hence expected global benefit under ET,

$$B := \mathrm{E}[\tilde{B}] = -\tfrac{1}{2}Mp^2 + VMp. \qquad \text{[R3.3]}$$

Setting $dB/dp = 0$ then shows that expected global benefit is maximised when the targets set are such that the expected permit trading price [3.9] is the sum of each country's valuations:

B achieves its maximum value of $\tfrac{1}{2}V^2M$ when $p = V = \Sigma V_i$. [R3.4]

This illustrates Samuelson's (1954) principle for optimal pricing of a public good. At this optimal price, from [R3.2] and [R3.3], global net emissions uncertainty is all neutralised, and realised benefit equals expected benefit:

$$p(\mathbf{x}) = V \;\Rightarrow\; \tilde{B} = B. \qquad \text{[R3.5]}$$

Referees' Appendix 4: Derivation of [3.77]

From [2.39],

$$\tilde{u}_i = \tilde{g}_i + (1-e^{-r\tilde{G}_i})/Y_i, \text{ which from [3.63]}$$

$$= g_i + (H_i/L_i)\tilde{T}_{-i} - [(p-H_i)/L_i]\tilde{T}_i$$

$$+ (1-e^{-r\{G_i + H_i\tilde{T}_{-i} - (p-H_i)\tilde{T}_i\}})/Y_i. \qquad [R4.1]$$

This is exactly the same as [3.66], except for these changes in parameters: $G_i \rightarrow g_i$ and $y_i \rightarrow Y_i$. So a transformed version of [3.67] that gives expected per capita payoff [2.44] is

$$E[\tilde{u}_i] = g_i + (1-e^{\frac{1}{2}r^2\Gamma_i^2 - rG_i})/Y_i = E[\tilde{U}_i] / L_i, \qquad \text{as in [3.77].}$$

Referees' Appendix 5: Proof that making net benefit quadratic in abatement would not make gain dependent on degree of intensity

Suppose that instead of [2.33], country *i*'s net benefit from climate action with financial surplus F_i and global abatement Q was

$$B_i'(F_i,Q) := F_i + V_iQ - \tfrac{1}{2}R_iQ^2, \quad R_i > 0 \text{ some parameter.} \qquad [R5.1]$$

so that [3.23] and [3.33] then become

$$\tilde{B}_i' := \tilde{p}\tilde{S}_i - \tilde{C}_i + V_i\tilde{Q} - \tfrac{1}{2}R_i\tilde{Q}^2 = \tilde{B}_i - \tfrac{1}{2}R_i\tilde{Q}^2, \text{ and} \qquad [R5.2]$$

$$\hat{B}_i' := -\hat{C}_i + V_i\hat{Q} - \tfrac{1}{2}R_i\hat{Q}^2 = \hat{B}_i - \tfrac{1}{2}R_i\tilde{Q}^2. \qquad [R5.3]$$

Expression [3.25] for $\tilde{B}_i$ from Full ET then becomes

$$\tilde{B}_i' = B_i + H_i\tilde{T}_{-i} - (p-H_i)\tilde{T}_i - \tfrac{1}{2}R_i\tilde{Q}^2, \text{ which from [3.18] and [3.17]}$$

$$= B_i + H_i\tilde{T}_{-i} - (p-H_i)\tilde{T}_i - \tfrac{1}{2}R_i(p+\tilde{T}/M)^2M^2$$

$$\approx B_i + H_i\tilde{T}_{-i} - (p-H_i)\tilde{T}_i - \tfrac{1}{2}R_i(p^2M^2+2pM\tilde{T})$$

$$= B_i - \tfrac{1}{2}R_ip^2M^2 + H_i\tilde{T}_{-i} - (p-H_i)\tilde{T}_i - R_ipM(\tilde{T}_{-i}+\tilde{T}_i)$$

$$= B_i' + H_i'\tilde{T}_{-i} - (p-H_i')\tilde{T}_i, \qquad [R5.4]$$

where

$$B_i' \;:= B_i - \tfrac{1}{2}R_i p^2 M^2 \;\text{ and }\; H_i' := H_i - R_i pM. \qquad \text{[R5.6]}$$

To compute the Unilateral case, from [R5.3] and [3.33], country i would now choose $\overset{\vartriangle}{Q}_i$ to maximise

$$\overset{\vartriangle}{B}_i' \;:=\; -\tfrac{1}{2}(\overset{\vartriangle}{Q}_i)^2/M_i + V_i\overset{\vartriangle}{Q} - \tfrac{1}{2}R_i\overset{\vartriangle}{Q}^2 \qquad \text{[R5.7]}$$

instead of [3.33]. Hence

$$\partial\overset{\vartriangle}{B}_i'/\partial\overset{\vartriangle}{Q}_i = -\overset{\vartriangle}{Q}_i/M_i + V_i - R_i\overset{\vartriangle}{Q} = 0$$

$$\Rightarrow \overset{\vartriangle}{Q}_i = V_iM_i - R_iM_i\overset{\vartriangle}{Q}, \;\text{ which on summing} \qquad \text{[R5.8]}$$

$$\Rightarrow \overset{\vartriangle}{Q} = \Sigma V_kM_k - \Sigma R_kM_k\overset{\vartriangle}{Q}$$

$$\Rightarrow \overset{\vartriangle}{Q} = \hat{Q} := \Sigma V_kM_k/(1+\Sigma R_kM_k). \qquad \text{[R5.9]}$$

(Note that Unilateral abatement is again certain, not uncertain.) So from [R5.7] and [R5.8],

$$\begin{aligned}\overset{\vartriangle}{B}_i' \;&:=\; -\tfrac{1}{2}(V_iM_i - R_iM_i\hat{Q})^2/M_i + V_i\hat{Q} - \tfrac{1}{2}R_i\hat{Q}^2\\ &= -\tfrac{1}{2}V_i^2M_i + V_iR_iM_i\hat{Q} - \tfrac{1}{2}R_i^2M_i\hat{Q}^2 + V_i\hat{Q} - \tfrac{1}{2}R_i\hat{Q}^2\\ &= -\tfrac{1}{2}V_i^2M_i + (V_i\hat{Q} - \tfrac{1}{2}R_i\hat{Q}^2)(R_iM_i+1), \qquad \text{[R5.11]}\end{aligned}$$

which is also certain. Hence from [2.37], [R5.4] and [R5.11],

$$\tilde{G}_i' \;= B_i' + H_i'\tilde{T}_{-i} - (p - H_i')\tilde{T}_i + \tfrac{1}{2}V_i^2M_i - (V_i\hat{Q} - \tfrac{1}{2}R_i\hat{Q}^2)(R_iM_i+1).$$

[R5.12]

With [R5.6], this means

$$G_i' \;:= \mathrm{E}[\tilde{G}_i'] = B_i - \tfrac{1}{2}R_i p^2M^2 + \tfrac{1}{2}V_i^2M_i - (V_i\hat{Q} - \tfrac{1}{2}R_i\hat{Q}^2)(R_iM_i+1).$$

[R5.13]

With B_i defined as in [3.26], p as in [3.9] and $\hat{Q}$ as in [R5.9], we then see that there is no presence of β_i in any term in [R5.13]. So we have shown as required that even with a quadratic benefit function, country i's expected gain G_i' still does not depend on the intensity index of its emissions target.