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Tax-Versus-Trading and Free Emission Shares as Issues for Climate Policy Design

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ABSTRACT

We give empirical welfare results for global greenhouse gas emission control, using the first multi-party model to combine tax-versus-trading under uncertainties with revenue recycling. Including multiple parties greatly reduces the welfare advantage of an emissions tax over emissions (permit) trading in handling abatement-cost uncertainties, from that shown by existing, single-party literature. But a tax has a different, much bigger advantage, from better handling uncertainties in business-as-usual emissions. Either mechanism's free emissions share, from tax thresholds or free permits, which lowers its possible welfare gain from revenue recycling, may however dominate any tax-versus-trading advantage. Moreover, political and practical constraints, such as the political unacceptability of no free emissions, the institutional unavailability of efficient emissions tax thresholds, and the unpopularity of recycling revenue as conventional tax cuts, make ideal welfare maximisation a poor guide for mechanism choice; and at optimal prices, trading currently tends to outperform taxation.

JEL codes: D810, H230, Q580
Keywords: climate policy, emission pricing, tax vs. trading, uncertainties, revenue recycling, political economy

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1. INTRODUCTION

Designing policy mechanisms for abating greenhouse gas emissions cost-effectively grows ever more important, as scientists give ever stronger warnings of the abatement urgently needed to avoid dangerous climate change (Richardson et al. 2009). For decades economists have promoted emission pricing − market mechanisms (or economic instruments) like a carbon (emissions) tax or (carbon) emissions (permit) trading − for such abatement. This is because compared to directly regulating millions of greenhouse emitters, emission pricing can minimise total abatement costs, by equalising emitters' initially very diverse marginal abatement costs, and can avoid huge administration costs.

Also for decades, economists have debated which abatement pricing mechanism is generally most cost-effective, especially the choice between direct "prices" (a tax) and indirect prices via "quantities" (tradable permits) under abatement-cost uncertainty, following Weitzman (1974). Since the early 1990s, another issue in this debate as applied to greenhouse control has been the welfare-reducing interaction between emission pricing and conventional, presumably distortionary taxes on labour or capital. This has highlighted the importance of recycling revenue from emission pricing as lower rates of conventional taxation (Goulder 1995). Yet a mechanism which maximises welfare (and hence cost-effectiveness) in a model may well be politically unacceptable or institutionally unavailable, and thus of little practical use. Our general contribution is to combine a new model of global greenhouse emission pricing with a review of climate policies in practice, to help determine the economically best mechanism which is also acceptable and available.

Our model is the first multi-party, theoretical and empirical model of greenhouse gas control combining tax-vs-trading (though here with multiple uncertainties, not just in abatement costs) and revenue recycling (as conventional tax cuts). Quirion (2004) is the only other combination of tax-vs-trading and revenue recycling, and his model was only theoretical and for one party. Our inclusion of many parties (firms or countries) is remarkably rare: a rarity perhaps caused by Weitzman's prices-vs-quantities welfare formula, which the well-known empirical literature citing him uses, being for a *single*, hence non-trading, party. But any real emissions-pricing scheme contains many parties, whose diversity of abatement costs is the main justification for emission pricing, as already noted.

We proceed by adding a tax and an approximate revenue-recycling formula to the multi-party, numerically solved, mainly partial equilibrium model of Mechanisms to Abate Total Emissions under Stochasticity (MATES) in Jotzo and Pezzey (2007), and computing the tax-vs-trading and revenue-recycling welfare differences. Hybrid mechanisms, such as emissions trading subject to a price cap (Pizer 2002, based on ideas originally in Roberts and Spence 1976) or long-term permits combined with a short-run maximum price (McKibbin and Wilcoxen 2002), among many others, could be important extra practical options, but the main issues here would still be relevant. Our empirical context is an 18-region world in 2020, representing a short run when the global greenhouse gas stock is implicitly huge compared to emissions, so the marginal abatement benefit curve is very flat.

Our multi-party approach alters the tax-vs-trading welfare advantage under abatement-cost uncertainty from that in well-cited authors like Hoel and Karp (2001, 2002), Pizer (2002), Montero (2002) and Newell and Pizer

(2003, 2008), who used a single (representative) party model.[1] However, our novel inclusion of uncertainties in each party's (country's or region's) future, business-as-usual emissions, as well as in their abatement costs, also changes the advantage. A further, quite different welfare effect modelled is the advantage of recycling tax or permit revenue as conventional tax cuts. This obviously falls as either mechanism's "free emissions share" (the share of emissions covered by tax thresholds or free permits) rises, and *may* dominate any tax-vs-trading advantage − the 'may' needed because the size of this effect is now so contentious (Wendner and Goulder 2008).

In any case, welfare results alone are insufficient to choose the economically best emission pricing mechanism which is also acceptable and available, as we show by discussing political and institutional constraints on such choices. Space, and to some extent the subject matter, precludes any formal empirical modelling, so our findings here are inevitably less rigorous and more debatable, but arguably no less important than our welfare results. We first give evidence that a zero free emissions share is politically unacceptable, unless the emission price and abatement are far below optimal. We then note how using tax thresholds as quasi-property rights, so a tax can allow some free emissions yet retain long-run efficiency (Mumy 1980, Pezzey 1992, Farrow 1995, Pezzey 2003), is institutionally

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[1] Our multi-party formula, discovered independently, is actually a special case of results for imperfectly mixed emissions in Williams' (2002) working paper; but he put no emphasis on the multi-party question and gave no empirical results. None of the few papers citing Williams even used his multi-party formula; Krysiak (2008) had a firm-specific random variable, but no certain variation in marginal abatement cost across firms. A multi-party tax-vs-trading advantage can be computed from results in Mandell (2008), but only for a specific form of cross-party variation in marginal abatement cost slopes.

unavailable so far, because this idea has been very largely ignored by economists, and completely ignored by policymakers. We next observe that two other common modelling assumptions in MATES − that all revenue recycling is in the form of tax cuts, and no economic sectors are excluded from emission pricing − are rarely true in practice. Finally, we discuss the complex effects of all these constraints on current mechanism choice, and their implications for future research.

The paper is organised as follows. Section 2 presents the theoretical model, and discusses the resulting formulae for multi-party tax-vs-trading advantage and revenue-recycling effect. Section 3 gives empirical welfare results, and Section 4 discusses political and institutional constraints on applying them to climate policy. Section 5 concludes.

2. A MODEL WITH TAX-VS-TRADING AND FREE EMISSIONS SHARES

2.1 The theoretical model

Emissions are perfectly mixed in a common environment used by n unevenly sized parties (firms, countries, or regions of countries) indexed by $i = 1,...,n$. An absent subscript i means summation over all parties (so $Z := \Sigma_i Z_i$ for any $\{Z_i\}$); while a tilde, $\tilde{}$, means an uncertain (stochastic) variable, and its absence denotes an expectation (so $Z_i := \mathrm{E}[\tilde{Z}_i]$). Each party's business-as-usual (BAU), uncertain emission in say tonnes/year (t/yr) at a single future date is:

$$\tilde{E}^b_i \quad = E^b_i(1+\varepsilon_{Ei}), \text{ where} \qquad [1]$$

ε_{Ei} = proportional uncertainty in i's emission,[2]

and importantly, all errors are assumed independent with zero means:

$$\mathrm{E}[\varepsilon_{Ei}\varepsilon_{Ek}] = 0 \;\; \forall \; i{\neq}k, \;\; \mathrm{E}[\varepsilon_{Ei}] = 0, \;\text{ and }\; \mathrm{E}[\varepsilon_{Ei}{}^2] =: \sigma_{Ei}{}^2. \qquad [2]^3$$

Each party abates its emissions by an uncertain $\tilde{Q}_i$ in response to a tax or emissions trading system created by an "authority" (a global treaty or a national law, with full participation and enforcement always assumed). We will compare the market-wide (i.e. social) net benefits for each mechanism of achieving a given target X for expected total emissions:

$$X = \mathrm{E}[\Sigma_i(\tilde{E}^b{}_i - \tilde{Q}_i)] = E^b - Q, \qquad [3]$$

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[2] In estimating $\mathrm{E}[\varepsilon_{Ei}{}^2]$ empirically, Jotzo and Pezzey (p263) used emissions uncertainties from three separate sources: uncertainties in GDP, in emissions intensities of GDP, and in non-GDP-linked emissions.

[3] The effect of positive cross-party correlations in BAU emissions, as surely happened in the 2008 global recession, is separately addressed below.

given that each party's uncertain abatement cost is $\tilde{C}_i(\tilde{Q}_i)$ in say \$/yr.[4]

With an *emissions tax*, denoted ^{P} for *P*rice, the authority chooses a certain tax rate p^P (in \$/t) so that Q, the expected sum of abatements $\tilde{Q}_i(p^P)$ − which each party chooses to equate its marginal abatement cost (MAC) $\tilde{C}_i'(\tilde{Q}_i)$ with rate p^P − equals the expected abatement task, $E^b - X$ (assumed positive). The authority also gives party i a tax threshold ϕX_i ($0 \leq \phi \leq 1$, $X_i > 0$) as a quasi-property right.[5] This preserves long-run efficiency by making p^P apply to emitters' exit-entry decisions, and under certainty is symmetric with free tradable permits (Pezzey 1992, who called the tax threshold a "baseline for a charge-subsidy"). A threshold ϕX_i is thus an inframarginal tax exemption for i, as distinct from exempting i completely from the tax, which is here called an *exclusion*. Exclusions and *dilutions* (lower rates for selected sectors) are frequent practical occurrences (see for example Svendsen et al. 2001), but they remain outside our model.

With *emissions trading*, denoted ^{T}, the authority creates X tradable permits (again $< E^b$), gives each party ϕX_i free permits, and auctions the remaining $(1-\phi)X$ permits.[6] Permit trading then establishes an uncertain

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[4] We thank a referee for noting that welfare maximisation for a tax and for trading do not necessarily result in the same expected abatement Q, unless marginal abatement costs and benefits are linear, as in fact we assume below.

[5] The only constraint on the $\{X_i\}$ here is $\Sigma_i X_i = X$, so assuming the same ϕ for all parties still allows the authority to choose the distribution $\{\phi X_i\}$ on political grounds.

[6] Jotzo and Pezzey's uncertain targets $\{\tilde{X}_i\}$ included intensity (indexed) targets; see also Newell and Pizer (2008). However, this extension would distract from the focus here on tax-versus-trading versus free emissions share.

permit price $\tilde{p}^T$, and each party chooses abatement $\tilde{Q}_i(\tilde{p}^T)$ to equate its MAC $\tilde{C}_i'(\tilde{Q}_i)$ to this price. Permit-market clearing ensures that total abatement $\tilde{Q}(\tilde{p}^T)$ equals the required abatement task $\tilde{E}^b-X$.

In either case, ϕ is called the *free emissions share*, and denoting either tax p^P or permit price $\tilde{p}^T$ by $\tilde{p}$, the authority gets revenue $\tilde{R}_i := \tilde{p}[\tilde{E}^b_i-\tilde{Q}_i(\tilde{p})-\phi X_i]$ from party i. This will be negative if party i's abated emissions fall below its threshold or free permit level ($\tilde{E}^b_i-\tilde{Q}_i(\tilde{p}) < \phi X_i$), but we assume that total revenue $\tilde{R}$ is positive (by choosing ϕ low enough), and also fully recycled as lower rates of conventional taxation.

The authority uses a market mechanism to induce abatement in order to achieve environmental benefits for parties and thus raise welfare. Given perfect emission mixing, party i's benefit depends on total abatement $\tilde{Q}$, and is denoted $\tilde{B}_i(\tilde{Q})$ (\$/yr). We then take the approximate net *social* benefit attributable to party i of abatement, compared to zero abatement everywhere, to be

$$\tilde{A}_i(\tilde{Q},\tilde{Q}_i) := \tilde{B}_i(\tilde{Q}) - \tilde{C}_i(\tilde{Q}_i) - \mu[\tilde{C}_i(\tilde{Q}_i)+\tilde{p}\phi X_i], \qquad [4]^7$$

and assume the authority chooses parameters so as to maximise risk-neutral *welfare*, defined as expected total net benefit A (= $\mathrm{E}[\Sigma_i\tilde{A}_i]$). Here $\mu > 0$ is the marginal excess burden of public funds caused by conventional, distortionary taxation. This gives rise to two approximate general equilibrium social costs: $\mu\tilde{C}_i(\tilde{Q}_i)$ from emission price $\tilde{p}$ interactions with the conventional tax, and $\mu\tilde{p}\phi X_i$ from lost revenue-recycling benefit caused

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[7] As in Weitzman, party i's payment $\tilde{R}_i$ is not deducted because it is a wealth transfer to the authority which does not affect global, risk-neutral welfare. (Jotzo and Pezzey included $\tilde{R}_i$ because they also considered risk aversion.)

by the free emissions share ϕ (from Quirion 2004, p342, whose $\mu-1$ equals our μ, and his source, Goulder et al. 1999, pp341-2 and unpublished appendix). These costs are approximate partly because they assume linear demand, supply and marginal cost curves; but also because the size and even sign of μ is now so contentious (Wendner and Goulder 2008, see Section 3.1 below), which makes the ideal procedure of numerically solving a full general equilibrium model of little extra value. For any greenhouse gas application, μ will obviously vary across parties (countries), but to keep our analysis tractable we need to assume all $\mu_i = \mu$.

Finally, we assume quadratic cost and benefit functions:

$\tilde{C}_i(\tilde{Q}_i) \quad := \tfrac{1}{2}(1/M_i)\tilde{Q}_i^{\,2} + \varepsilon_{Ci}\tilde{Q}_i$, where [5][8]

$\{M_i\}$ ($\mathrm{t}^2/\$.\mathrm{yr}$) > 0 are parameters, and $1/M$ is the slope of the total MAC curve;

ε_{Ci} ($/t) is *i*'s uncertainty in MAC, with

$\mathrm{E}[\varepsilon_{Ci}] = 0$ and $\mathrm{E}[\varepsilon_{Ci}^{\,2}] = \sigma_{Ci}^{\,2}$ for all i, and each ε_{Ci} is assumed independent of all other uncertainties in the model. [6]

$\tilde{B}_i(\tilde{Q}) \quad := V_i\tilde{Q} - \tfrac{1}{2}W_i\tilde{Q}^2$, where [7]

V_i ($/t) > 0, W_i ($\$.\mathrm{yr}/\mathrm{t}^2$) > 0. V will be called the *linear valuation* of

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[8] This additive form of uncertainty shifts the MAC curve ($\tilde{C}_i'(\tilde{Q}_i) = (1/M_i)\tilde{Q}_i + \varepsilon_{Ci}$) up or down by ε_{Ci}, as in Weitzman (eq. (10)) and many authors since. A referee noted that then $\tilde{C}_i'(0) = \varepsilon_{Ci}$, meaning that MAC could be negative at zero abatement. An alternative which avoids this awkward possibility would be to assume multiplicative uncertainty, as in Hoel and Karp (2001) and Quirion (2005). We still use [5], both to make our results comparable to the Weitzman-inspired literature, and because we deal only with large-abatement situations where MAC < 0 is extremely unlikely.

abatement, while W is the slope of the total marginal abatement benefit (MAB) curve.[9]

From [5] and [7], the net social benefit [4] attributable to party i is then

$$\tilde{A}_i = V_i\tilde{Q} - \tfrac{1}{2}W_i\tilde{Q}^2 - (1+\mu)[\tfrac{1}{2}(1/M_i)\tilde{Q}_i^{\,2} + \varepsilon_{Ci}\tilde{Q}_i] - \mu\phi X_i\tilde{p}. \qquad [8]$$

We can then show (see Appendix) that maximising welfare A (expected total net social benefit) results in:

optimal, expected welfare from an emissions *tax*:

$$A^P = A^* + \tfrac{1}{2}\Sigma_i[(1+\mu)/M_i - \quad W \quad]M_i^2\sigma_{Ci}^2; \qquad [9]$$

optimal, expected welfare from emissions *trading*:

$$A^T = A^* + \tfrac{1}{2}\Sigma_i[(1+\mu)/M_i - (1+\mu)/M]M_i^2\sigma_{Ci}^2$$
$$- \tfrac{1}{2}[(1+\mu)/M+W]\Sigma_i(E^b_{\ i})^2\sigma_{Ei}^2; \qquad [10]$$

where the optimal welfare under *certainty* from either mechanism is

$$A^* := \tfrac{1}{2}(V - \mu\phi E^b/M)^2M \;/\; [1+(1-2\phi)\mu+WM]. \qquad [11]$$

Hence the *tax-vs-trading* (welfare) *advantage* is

$$\Delta := A^P-A^T = \tfrac{1}{2}[(1+\mu)/M - W]\Sigma_iM_i^2\sigma_{Ci}^2 + \tfrac{1}{2}[(1+\mu)/M+W]\Sigma_i(E^b_{\ i})^2\sigma_{Ei}^2; \; [12]$$

while the optimal, expected emission price and total abatement are

price $p^* = (V - \mu\phi E^b/M) \;/\; [1+(1-2\phi)\mu+WM]$, abatement $Q^* = Mp^*$. [13]

For reasons given later, we also write the emissions-trading welfare including only abatement-cost uncertainties ([10] minus the last term) as

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[9] We ignore any shift stochasticity in i's MAB, which does not affect the tax-vs-trading comparison. We thus also ignore any correlations between MAB and MAC uncertainties, which do affect the comparison (Stavins 1996). For nations emitting GHGs, there is no evidence for such correlation.

$$A^T_C := A^* + ½\Sigma_i[(1+\mu)/M_i - (1+\mu)/M]M_i^2\sigma_{Ci}^2. \qquad [14]$$

In addition, if emission uncertainties are correlated rather than independent across parties, so that $E[\varepsilon_{Ei}\varepsilon_{Ek}] =: \sigma_{Eik} \neq 0$ for several $i \neq k$, then $\Sigma_i(E^b_i)^2\sigma_{Ei}^2$ in [10] and [12] is replaced by $\Sigma_i(E^b_i)^2\sigma_{Ei}^2 + 2\Sigma_{i\neq k}E^b_iE^b_k\sigma_{Eik}$ (see Appendix). Assuming positive correlations outweigh negative ones ($\Sigma_{i\neq k}E^b_iE^b_k\sigma_{Eik} > 0$), as seems reasonable in the 2008 global recession, this increases the tax-vs-trading advantage.[10] However, we have no data for $\{\sigma_{Eik}\}$, and thus no empirical results for correlation effects.

Another caveat is that we assume above that when $\mu > 0$,

$$\phi < VM/\mu E^b, \text{ so that } p^* > 0; \qquad [15]$$

for without a free emissions share ϕ small enough to make the optimal price p^* positive, a small cut in emissions actually lowers welfare, as stressed by Goulder et al. (1999). For plausible values of ϕ and μ, the single-party version of [15] fails for all regions in the MATES case study for greenhouse abatement. This gives one justification for our ignoring, by using expected total net benefit A in [8]-[9] as our measure of a mechanism's added welfare, the possibility that a single party (especially a large one) might abate unilaterally.[11] The other justification is that the papers with which we compare our results below also ignore any possibility of unilateral abatement. However, for the global aggregate, [15] is a feasible though non-trivial constraint.

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[10] We thank a referee for this point.

[11] See Jotzo and Pezzey (2007) for formulae and results for a market mechanism's gain in expected net benefit compared to unilateralism.

2.2 Features of the total expected welfare results

Three features of the above results deserve further comment. The first is that the free emissions share ϕ affects only the certainty component A^* in [11], not the tax-vs-trading advantage Δ in [12]. So in principle the choice of free emissions shares is separate from the tax-vs-trading choice. In practice, though, current institutional and political realities dictate that the two choices are tightly connected, and in our view are best discussed together, as we do in Section 4.

The second feature is that uncertainty in parties' emissions adds $\tfrac{1}{2}[(1+\mu)/M + W]\ \Sigma_i (E^b_i)^2 \sigma_{Ei}^2$, the second term in [12], to the tax-vs-trading advantage. Intuitively, this arises from emissions uncertainty being a second source of emission price uncertainty under trading, and thus a second advantage of the fixed emission price under a tax. It deserves more attention because our global, greenhouse case study will show it easily dominates the first, well-known term in [12] arising from abatement-cost uncertainties.

The third feature is the extent to which including *multiple*, independent parties changes this first term, which we write as

$$\Delta_C := \tfrac{1}{2}[(1+\mu)/M - W]\Sigma_i M_i^2 \sigma_{Ci}^2. \qquad [16]^{12}$$

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[12] This independently reproduces Williams' (2002) result for the case of global (i.e. uniform) pollution. His wording (pp16-17) was: "When the goods are perfect substitutes [as with global pollution] ... expression (34) [for the tax-vs-trading advantage] will reduce to $\Delta^{TP} = -\ \Sigma_i(\sigma_i^2/2\gamma_{ii}^2)(\beta_{ii}+\psi)$". With converted notation and changed sign this is [16] when $\mu = 0$. We put no superscript on Δ because unlike Williams, we consider here only the P(tax)-vs-T(trading) advantage.

This is indeed an advantage ($\Delta_C > 0$) for short-run greenhouse emissions, because as noted for example by Pizer (1999, 2002), the large existing pollutant stock means the total MAB curve is very flat (so $W << 1/M$). But if a *single* representative party, denoted $_1$, is assumed, [16] becomes

$$\Delta_{C1} := \tfrac{1}{2}[(1+\mu)/M - W]M^2\sigma_C^2; \quad \text{hence} \quad \Delta_{C1}/\Delta_C = M^2\sigma_C^2 \,/\, \Sigma_i M_i^2\sigma_{Ci}^2; \quad [17]$$

and after converting notation and setting $\mu = 0$, Δ_{C1} *is the main result given by Weitzman (1974, eq. (20)).*[13] The ratio Δ_{C1}/Δ_C depends on the exact distribution of party sizes, but is probably much larger than one. If we simplify by assuming all $\sigma_{Ci}^2 = \sigma_C^2$ (as done in the empirical application of MATES, in the absence of better data[14]), two simple exact cases are $M_i = M/n$ (uniform) $\Rightarrow$ $\Delta_{C1}/\Delta_C = n$, and $M_i = M/2^i$ (exponential) $\Rightarrow$ $\lim_{n\to\infty}\Delta_{C1}/\Delta_C = 3$; while $\Delta_{C1}/\Delta_C \approx 9$ in our empirical model where $n = 18$. So the single-party formula Δ_{C1}, which ignores how trading dampens the transmission of many parties' (independent) cost uncertainties into uncertainty in the permit price, significantly overestimates the advantage of a tax over realistic permit trading.

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13. Weitzman did not give any multi-party trading formula, even though his footnote 1 on p490 clearly envisaged an application to emissions trading. His Section V on Many Production Units computed the many-party relative advantage of prices over *non*-traded quantities, as clarified by his remarking on p489 that "with quantities, [any two parties have different marginal abatement costs] except on a set of negligible probability". The same is true in Yohe (1976, Section IV).

14. σ_{Ci}^2 is the variance in marginal abatement costs, which on expectations is equal across countries. Hence any differences in vairance between countries would happen because of idiosyncratic factors such as economic structure and types of production technologies, not as a result of country size.

This matters, because the well-known, climate-related literature on prices-vs-quantities uses the single-party formula Δ_{C1} (with $\mu = 0$): see for example Hoel and Karp (2001, 2002); Pizer (2002, whose eq. (1) is Δ_{C1} in our notation with $\mu = 0$); Montero (2002); and Newell and Pizer (2003, 2008). As noted earlier, trading effects were developed theoretically by Williams (2002), and are obviously implicit in many empirical models. However, we could not find any empirical study of taxes versus permit trading for greenhouse emissions abatement which both uses Weitzman's theoretical foundation and allows for multi-party trading.

3. EMPIRICAL RESULTS FOR CLIMATE POLICY

3.1 Parameters chosen

Our empirical application of MATES is to static abatement of greenhouse emissions in 2020, in a world with 18 regions (countries or groups of countries), ranging in size from Argentina and Australia to the USA and Europe. The model parameters used in calculating results [9]-[11] for global expected welfare of an emissions tax or emissions trading are in **Table 1**. Jotzo and Pezzey (2007) explained how these numbers were calibrated empirically.

Table 1 Key global parameters in 2020 in the MATES model

($ = US$ in 2000; t = tonne of CO_2-equivalent)

Parameter	*Notation and value*
BAU greenhouse gas emissions	$E^b = 54.4$ Gt/yr ($= 1.3E_{2002}$)
Linear valuation of abatement	$V = 21.9$ \$/t
MAC slope	$1/M = 2.32$ (\$/t)/(Gt/yr)
MAB slope	$W = 0.22$ (\$/t)/(Gt/yr)
Uncertainty in abatement costs	$\Sigma_i M_i^2 \sigma_{Ci}^2 = 0.37$ (Gt/yr)^2
Uncertainty in BAU emissions	$\Sigma_i (E^b_i)^2 \sigma_{Ei}^2 = 11.35$ (Gt/yr)^2

The last two numbers used in our model are given as choices, because they are unavoidably more contentious in their empirical estimation (for μ) or their political implications (for ϕ):

marginal excess burden, $\mu = 0$ or 0.2 for all regions; [18]

free emissions share, $\phi = 0$ or 0.5 for all regions. [19]

We give two values for μ because empirical estimates of this parameter are indeed now so contentious. Important research by Wendner and Goulder (2008) included the need for a consumption tax to correct status (relative consumption) externalities, and found it plausible that 20-40% of marginal utility comes from status in rich countries. With a consumption tax rate ranging from 20-50%, they then estimated a range of μ from −0.27 to 0.91, depending on other parameters chosen, significantly lower than previous authors'. Given the worldwide diversity of income and taxation, ignored by our simplifying assumption of a common μ, and an earlier tendency of authors like Goulder et al (1999) to use $\mu = 0.3$ as a "benchmark", we think the values $\mu = 0$ or 0.2 give a useful range of results for discussion.

The free emissions share ϕ is chosen by national governments under strong political constraints. Most economists assume $\mu > 0$, hence a potential revenue-recycling effect, and thus recommend no free emissions share ($\phi = 0$) on welfare grounds. But governments typically find it difficult to resist industry lobbying to give away a sizeable share of tradable permits for free, at least initially (discussed further in Section 4.1 below). So $\phi = 0$ or 0.5 seem useful choices to consider, without prejudging which value may be most realistic in a particular setting.

3.2 Results

Results in **Table 2** come from inserting values from Table 1, [18] and [19] into formulae [9]-[14]. The results' significance for mechanism choice is complex, as discussed in Section 4; here we just clarify how they were computed.

Table 2 MATES results for global greenhouse abatement in 2020

<table>
<tr><td colspan="2">μ, marginal excess burden</td><td>0</td><td colspan="2">0.2, with all revenue recycled as cuts in conventional tax rates</td></tr>
<tr><td colspan="2">ϕ, free emissions (tax thresholds or free tradable permits) share of global target</td><td>(irrel-evant)</td><td>0 ("pure" mechanism)</td><td>0.5</td></tr>
<tr><td colspan="5">Welfare in 2020 (expected global net benefit in US2000 G$/yr) from:</td></tr>
<tr><td colspan="2">Optimal emissions tax with thresholds (A^P)</td><td>98.1</td><td>84.3</td><td>21.5</td></tr>
<tr><td colspan="2">Optimal emissions trading with abatement-cost and emissions uncertainties (A^T)</td><td>83.3</td><td>66.8</td><td>3.9</td></tr>
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<tr><td colspan="2">abatement-cost uncertainties only, single-party (Δ_{C1})</td><td>3.4</td><td colspan="2">4.2</td></tr>
<tr><td colspan="5">Welfare lost from free emissions share, ($A^*(\phi=0.5) - A^*(\phi=0)$), with either optimal emissions tax or optimal emissions trading.</td></tr>
<tr><td colspan="2">− with standard linear valuation V</td><td>0</td><td></td><td>−62.8</td></tr>
<tr><td colspan="2">− with doubled linear valuation</td><td>0</td><td></td><td>−127.8</td></tr>
<tr><td colspan="5">Other optimal, expected global results (t = tonne of CO_2-equivalent)</td></tr>
<tr><td rowspan="2">For any optimal mechanism</td><td>Emission price p^* ($/t)</td><td>20.0</td><td>16.9</td><td>8.5</td></tr>
<tr><td>Abated emissions $E^b - Q^*$, c.f. BAU emissions in 2020</td><td>−16%</td><td>−13%</td><td>−7%</td></tr>
</table>

The first two lines of results show the welfare from an emissions tax (A^P in [9]) and emissions trading (A^T in [10]). Next comes the part of emissions trading welfare that includes only abatement-cost uncertainties ($A^T{}_C$ in [14]).

Our later discussion of these results focuses on welfare advantages from tax-versus-trading or from changes in the free emissions share, so the next two sections of Table 2 show:

- Three tax-vs-trading advantages − complete (Δ in [12]), with only abatement-cost uncertainties counted (Δ_C in [16]), and also assuming only one country (Δ_{C1} in [17]). No different V or ϕ values are shown, since neither parameter affects the Δ formulae. The third, Δ_{C1} row corresponds to well-known empirical literature; while the multi-party advantages Δ_C above are about 9 times smaller, because of the dampening effect of trading on permit price uncertainty, as discussed after [17]. Yet the full advantages with all uncertainties modelled by MATES, Δ, are much larger, because of the dominance (shown in Table 1) of emissions uncertainties over abatement-cost uncertainties.
- The approximate advantage lost by choosing a free emissions share $\phi = 0.5$ instead of 0 ($A^*(\phi)-A^*(0)$ from [11]), with a sensitivity test for doubling the linear valuation, V. Note how the lost advantage is zero if $\mu = 0$, and for non-zero μ, gets more negative with higher V; and with $\mu = 0.2$, the standard welfare loss of 62.8 G$/yr far exceeds the largest tax-vs-trading advantage of 17.5 G$/yr.

The Table's last two rows show, for comparison with current policy debates, how $\mu = 0$ or 0.2 and $\phi = 0$ or 0.5 affect the optimal emission price p^* from [13], and abated emissions as percentage cuts below projected

BAU emissions in 2020. The range of 7-16% global abatement below BAU is modest compared to current climate policy aims (Richardson et al. 2009); and the abatement cost associated with Q^* (not shown) is about 0.1% of MATES’ projected global GDP in 2020, reassuring us that this particular case study is an acceptable application of our mainly partial equilibrium model.

4. POLITICAL AND INSTITUTIONAL CONSTRAINTS ON THE CHOICE OF CLIMATE POLICY MECHANISMS

What do our results in Table 2 mean for practical choices of market mechanisms for climate policy? The implications are complex, because of political and institutional constraints. Here we review our results in the light of what recent policy developments reveal about the political unacceptability of no free emissions share with either tax or trading; the institutional unavailability of efficient tax thresholds; and the difficulty of full revenue recycling and making few exclusions with trading. The first two ideas were in Pezzey (2003), but none of the selected evidence below was in that paper. The arguments here are inevitably less rigorous than in a formal model like MATES, but they are arguably no less important.

4.1 The political unacceptability of no free emissions share

When the marginal excess burden $\mu > 0$, the highest welfare results in Table 2 are for an optimal tax with no thresholds, followed by optimal emissions trading with no free permits, because such "pure" mechanisms (with no free emissions share, $\phi = 0$) maximise revenue-recycling benefits.[15] But optimal, pure mechanisms are politically unacceptable and thus unlikely to be enacted, for the very same reason: because they raise very large amounts of government revenue (in our global greenhouse

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[15] As stressed by Nordhaus (2007, pp39-40) for a tax, pure mechanisms would also avoid wasteful rent-seeking because they have no permits or thresholds to distribute. However, this would be partly offset by a correspondingly greater incentive to seek rents from redistributed tax revenues.

example, roughly 1% of GDP[16]). Proposals to raise such amounts have always been defeated by the concentrated lobbying power of the greenhouse-intensive firms most strongly affected by emission pricing, as predicted by Olson (1965). This happens even though their cost increases can be mostly passed on to customers and suppliers, so that high enough free emission shares can produce windfall profits for emitters (Bovenberg and Goulder 2001, Sijm et al. 2006, Goulder et al. 2009).

Evidence for this assertion includes these examples:

- Early 1990s European proposals for a carbon/energy tax had no thresholds, and were eventually dropped, partly as a result of industry resistance to the large revenues that would have been raised (Jaeger et al. 1997, p196).
- In 2005, the New Zealand government proposed a carbon tax with no thresholds, and all revenue recycled into reducing existing taxes. A review scrapped the tax plan, with the key reason given being its unfairness and its inefficiency, with both caused by its large exclusions (NZCCO 2005). It is likely these exclusions were proposed to improve the tax's political acceptability, given its lack of thresholds. (*Exclusions* here means outright exemptions, where some emitters pay no tax on any emissions, and so have no marginal incentive to abate, unlike with a tax threshold. To call these *exemptions* would be ambiguous because some authors like Parry (2003) and Stavins (2008) used that to mean exempting some inframarginal emissions while charging tax on marginal

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[16] From Tables 1 and 2, expected price p^* times abated emissions $E_b - Q^*$ is 20.0 × (54.4×0.84) = 915 G$/yr for $\mu = 0$, and 16.9(54.4×0.87) = 796 G$/yr for $\mu = 0.2$. Global GDP, assuming growth of 3%/yr from 2008, would be 87 T$/yr by 2020. However, the abatement cost is much smaller than total tax or permit revenue.

emissions, which is close to the tax threshold idea.)

- In Australia’s climate policy development during 2007-9, an initial recommendation by a government-appointed review (Garnaut 2008) was for no free permits in a proposed emissions trading scheme. This was followed by a government consultative (Green) paper proposing a maximum free permit share of ϕ = 30%; and then by a government policy (White) paper proposing no maximum ϕ, and rules that could result in $\phi \approx 45\%$ (Australian Government 2008). In 2009 this was followed by more rises in the likely free permit share, in attempts to get the proposed legislation passed by parliament. Most of the free permit share is proposed for emissions-intensive, trade-exposed industries to discourage their relocation abroad (‘carbon leakage’), though the amount and method of distribution arguably gives much more assistance than necessary (Pezzey et al. 2010).
- The Obama administration’s early-2009 intention to auction 100% of permits ($\phi = 0$) in a U.S. emissions trading scheme was in stark contrast to the 15% permit auctioning proposed by the House (Waxman-Markey) bill passed in June 2009 and the initial 12% allowed in the 2010 Senate (Lieberman-Kerry) bill (Pew Center 2010).

Nevertheless, earlier presumptions of no permit auctioning (e.g. in Goulder et al. 1999) have now been largely replaced by acceptance of partial auctioning to raise revenue, and gradual progress towards more auctioning (e.g. in EU 2009). So a zero free emissions share is conceivable eventually; but attempting to introduce one now, at anything like an optimal emission price, is arguably doomed to fail.

4.2 The current institutional unavailability of emissions tax thresholds

A free emissions share is thus vital for making emission pricing, at optimal or near-optimal prices, politically acceptable. For a tax, this means using tax thresholds, ideally as quasi-property rights which maintain long-term efficiency, as noted in Section 2.1 and assumed by MATES. But tax thresholds are generally ignored by the climate economics literature, despite the common use of (non-property-right) thresholds in income taxes, and in water and energy pricing. This appears to be partly because long-term, exit-entry inefficiency, shown by Baumol and Oates (1988, Ch 14) to result from production-dependent emission control subsidies, is mistakenly considered to occur with the payments to emitters which may result from property-right (hence production-independent) thresholds, as noted before [4]. Almost all recent emissions tax analyses have followed earlier authors, like Buchanan and Tullock (1975) and Hahn (1989), by considering only a pure tax: see for example Goulder et al. (1999), Hoel and Karp (2002), Hepburn (2006), Nordhaus (2007) and Keohane (2009). None of these discussed the possibility that lower tax revenue might be politically more acceptable, and hence better, than the ideal (unattainable at any near-optimal tax rate) of full revenue-raising and recycling.

Of the few recent authors who have mentioned an efficient tax threshold, only Quirion (2004, p338) prominently discussed it (as a "baseline effluent right"), but such prominence is rare, and the following authors make only minor mentions. Parry (2003, p396) noted the idea of "exempting a small fraction of infra-marginal emissions from the tax base", as did Aldy et al. (2008, p502). Metcalf (2009a, p80) wrote that "a carbon tax [can provide] lump-sum transfers similar in impact to lump-sum distributions of free permits. A carbon tax, for example, could levy the tax on emissions above some threshold"; yet this idea was omitted from Metcalf (2009b) and Metcalf and Weisbach (2009). Stavins (2008, p350) accepted the threshold idea in theory, but doubted its practicality:

> "While tradable tax exemptions and redistributions of tax revenues theoretically provide flexibility to achieve the same distributional outcomes as could be achieved under a cap-and-trade approach, political and practical considerations may impose constraints on achieving similar outcomes in practice."

We share Stavins's doubts about current, though not potential, practicality. Because almost all writers ignore them or treat them as a minor issue, efficient emissions tax thresholds are thus far *institutionally* unavailable as a policy mechanism: policymakers remain ignorant of them, and there is no legal and administrative framework for the trading of tax thresholds. However, a framework might be readily developed from the emissions trading example, and this will surely happen faster if academic literature emphasises the similarities of efficient tax thresholds to free tradable permits; though the lag from Dales's (1968) seminal idea to the first fully-fledged emissions trading schemes suggests it might still take some years to move from theory to practice..

We predict that, partly because tax thresholds are currently unavailable, lobbying from emission-intensive sectors will ensure that any carbon tax scheme introduced soon will be at well below an optimal rate, as broadly happened with pollution taxation in Europe (Howe 1994), or will contain many sectoral exclusions or dilutions (Bohringer and Rutherford 1997, Ekins and Speck 1999), or both (Svendsen et al. 2001). So for combined institutional and political reasons, none of the welfare results in Table 2 for a tax (A^P) actually represent current policy options.

4.3 The difficulty of achieving full revenue recycling and no sectoral exclusions with emissions trading

The institutional availability of free permits as quasi-property rights makes optimal or near-optimal levels of abatement politically much more acceptable at present with emissions trading than with a tax. However, there are still big barriers to achieving two assumptions made in our modelling: full recycling of revenue as reduced conventional taxes, and making no sectoral exclusions. Permit revenue is rarely recycled as lower rates of conventional taxes in practice, for example:

- The prescribed purposes for how member countries should spend at least half of their revenues from the EU’s Emissions Trading Scheme do not include reducing conventional tax rates (EU 2009, Article 10(3)).
- Australia’s proposed emissions trading scheme would spend most permit revenue on supporting affected industries and direct transfers to low-income households, with some on supporting low-emissions technology and none on directly lowering distortionary taxes (Australian Government 2008).
- All revenue from Regional Greenhouse Gas Initiative (RGGI) auctions in the Northeastern USA is to be spent on clean energy projects (RGGI 2009).
- Both the U.S. Waxman-Markey and Lieberman-Kerry bills proposed to spend their revenue to support low-income households, rather than on reducing conventional tax rates (Pew Center 2010).

Recycling revenue as tax cuts thus has had little political appeal so far, which is rather surprising given its academic pedigree, and warrants further research. Other efficiency- or equity-enhancing ways of spending revenue − such as subsidising low-emission innovations, or compensating poor households and workers in emission-intensive industries − are clearly more appealing. Such compensations are arguably justified ethically, and may be more cost-effective than the sectoral exclusions from emission pricing that would otherwise be needed to make pricing politically acceptable. So full revenue recycling as tax cuts may not actually be a key criterion for good abatement policy.

Giving no or few sectoral exclusions from emissions trading, and thus creating a pervasive price on marginal emissions, is indeed crucial for welfare maximisation. The record here is mixed. Actual or proposed emissions trading schemes (ETSs) in Europe, the USA and Australia have excluded large sectors (notably some emissions-intensive manufacturers and final energy consumers), or given behaviour-linked free permits which dilute the effective price. But sectoral coverage was initially greater in the proposed US and Australian ETSs than in the original EU scheme, and is to expand under planned reforms of the EU ETS. In developing countries, prospects for pervasive pricing are quite distant, though gradually improving as climate negotiations progress. So MATES's assumption of no sectoral exclusions means our emissions trading results form only upper bounds on welfare gains that are achievable in practice.

4.4 Implications for mechanism choice

The above arguments show that focusing on only the tax-vs-trading welfare advantage, while ignoring the political economy of the free emissions share (ϕ), and the unavailability of efficient tax thresholds, can be misleading, possibly harmful. For on its own, the tax-vs-trading advantage in Table 2 points to a pure emissions tax as the best mechanism. But at anything like an optimal rate, this is politically unacceptable; while a tax with efficient thresholds (implicit in the Table when $\mu = 0$, explicit when $\phi = 0.5$) is institutionally unavailable. So the best mechanism in Table 2 which is currently acceptable and available is emissions trading with the lowest acceptable free permit share, ϕ (and no sectoral exclusions); and recommending a pure emissions tax instead may in fact be a barrier to welfare improvement.

The contentious value of the marginal excess burden μ does not change this current preference for emissions trading. It does however affect the importance of lowering the free permits share ϕ, because the approximate welfare loss from $\phi > 0$ in Table 2 rises roughly with $\mu\phi$, and with $\mu \approx 0.2$, a $\phi \approx 0.5$ can easily lose all the mechanism's welfare benefit. So a higher μ should strengthen an authority's resolve to keep ϕ low. But if μ is believed to be near zero, all that matters is keeping ϕ far enough below 1 to raise enough revenue to fund non-tax-cut purposes like compensation for badly affected people, or support for low-emissions technologies.

However again, our policy review also showed this preference for emission trading is not permanent, because further research and promotion, perhaps spurred by the overall quadrupling of the potential tax-vs-trading advantage shown in Table 2, could eventually make efficient tax thresholds institutionally available. (The same reasoning as above would then apply to keeping their share, ϕ, low.) It is also not a comprehensive preference, because of other mechanism options which have not yet been included in our modelling, including:

- using a suboptimal emission price, which should make a lower free emissions share ϕ politically more acceptable, with the net welfare effect dependent on μ;
- sectoral exclusions from, or dilutions of, a uniform emission price;
- inefficient tax thresholds or free permits (for example, those conditional on a party's production, instead of being quasi-property rights);
- non-tax-cut recycling purposes, which use up revenue that could otherwise be used for tax cuts.

So research is needed on how best to include these options in modelling (including further evidence on the value of μ), and also how to change the political economy of those options which prove most damaging to welfare.

5. SUMMARY AND CONCLUSIONS

We have introduced the first multi-party, theoretical and empirical model which combines the tax-versus-trading-under-uncertainty and revenue-recycling issues for pricing global emissions of greenhouse gases. We have used it to calculate the welfare advantage, given independent uncertainties in abatement costs and in business-as-usual emissions, of using a tax instead of a permit trading mechanism; and the approximate advantage of lowering the "free emissions share" (tax thresholds or free tradable permits, distributed as quasi-property rights, as a share of abated emissions), assuming that either mechanism's revenue is recycled as conventional tax cuts. Our model's theoretical results also apply to other well-mixed stock pollutants. We have also reviewed important political and institutional constraints on using ideal welfare maximisation to choose the best mechanism.

A key theoretical conclusion is that the short-run, welfare advantage of a tax over emissions trading in handling abatement-cost uncertainties for greenhouse gases has been much overestimated. Almost all literature here has used Weitzman's standard prices-vs-quantities formula, which is for a single (representative) party, instead of the appropriate multi-party formula, not explicitly given by Weitzman. Intuitively, the more parties with independent uncertainties in an emissions trading market, the less volatile is the trading price. A converse, empirical result is that for global greenhouse emissions, the tax-vs-trading welfare advantage arising from emissions uncertainties is many times larger than that from abatement-cost uncertainties; so overall, our results greatly boost this advantage.

A very different and more contentious welfare advantage comes from cutting the free emissions share, and recycling the increased tax or permit revenue as conventional tax cuts. This advantage is the same for tax or trading, and rises as the marginal excess burden of public funds rises. Mainly because of the wide range of estimates for the marginal excess burden in Wendner and Goulder (2008), but also because our welfare formula is approximate, reliable measurement of this revenue-recycling advantage remains elusive: it may dominate the tax-vs-trading advantage, or be negligible.

Our last section showed, though inevitably with less rigour than our modelling, that political and institutional constraints can make the best the enemy of the good: focusing solely on the tax-vs-trading advantage can be misleading, even harmful, as a practical guide to choosing a mechanism to improve welfare. The first constraint is that zero free emissions (no thresholds or free permits) causes too much revenue-raising to be politically unacceptable, unless the emission price and abatement are far below optimal. Next, using efficient (quasi-property right) tax thresholds to allow some free emissions is institutionally unavailable, because this idea has been largely ignored by economists, and completely ignored by policymakers. Finally, two of our other assumptions, common in economic models − that all mechanism revenue is recycled as conventional tax cuts, and no economic sector is excluded from emission pricing − are rarely true in practice.

The upshot of these constraints is that emissions taxes at optimal levels are ruled out as a realistic near-term policy, contrary to the recommendation arising from simple welfare maximisation. Instead, emissions trading with optimal expected prices and some free permits is the best pricing mechanism modelled here that is generally both acceptable and available.

But this is neither a permanent nor comprehensive conclusion: rather, one suggesting several research needs. In the short run, modelling should ideally be extended to include several features common in real-world market mechanisms, such as a suboptimal emission price, sectoral exclusions, and revenue being spent on non-tax-cut purposes. Estimates of the marginal excess burden need to be narrowed, to clarify the welfare value of revenue recycling for tax cuts. Political economy research needs to study how best to diminish those mechanism features which are most damaging to welfare. Finally, research into and promotion of tax thresholds as quasi-property rights is needed, if using taxation to control long-lived stock pollutants like greenhouse gases is to achieve its full potential, which our research shows is bigger than previously estimated.

APPENDIX

I. WITH ALL UNCERTAINTIES INDEPENDENT

For convenience, we repeat [8], the social net benefit for party *i*, as:

$$\tilde{A}_i = V_i\tilde{Q} - \tfrac{1}{2}W_i\tilde{Q}^2 - (1+\mu)[\tfrac{1}{2}(1/M_i)\tilde{Q}_i^2 + \varepsilon_{Ci}\tilde{Q}_i] - \mu\phi X_i\tilde{p} \qquad \text{[A1.1]}$$

For a *tax with thresholds*, where $\tilde{p} = p^P$, we combine the price-equals-MAC rule $\tilde{C}_i'(\tilde{Q}_i) = p^P$ and the quadratic total cost function in [5] to give

$$(1/M_i)\tilde{Q}_i + \varepsilon_{Ci} = p^P$$

$$\Rightarrow \tilde{Q}_i = M_i p^P - M_i\varepsilon_{Ci},\quad \tilde{Q} = Mp^P - \Sigma_i M_i\varepsilon_{Ci},\quad Q = Mp^P \qquad \text{[A1.2]}$$

$$\text{so} \quad \tilde{Q}_i^2 = (M_i p^P)^2 + (M_i\varepsilon_{Ci})^2 - 2M_i^2 p^P\varepsilon_{Ci}$$

$$\Rightarrow \mathrm{E}[\tilde{Q}_i^2] = M_i^2[(p^P)^2+\sigma_{Ci}^2] \qquad \text{[A1.3]}$$

$$\text{also} \quad \tilde{Q}^2 = (Mp^P)^2 - 2Mp^P\Sigma_i M_i\varepsilon_{Ci} + (\Sigma_i M_i\varepsilon_{Ci})^2$$

$$\Rightarrow \mathrm{E}[\tilde{Q}^2] = (Mp^P)^2 + \Sigma_i M_i^2\sigma_{Ci}^2 \quad \text{(using independence in [6])} \qquad \text{[A1.4]}$$

$$\text{also} \quad \varepsilon_{Ci}\tilde{Q}_i = \varepsilon_{Ci}M_i p^P - M_i\varepsilon_{Ci}^2$$

$$\Rightarrow \mathrm{E}[\varepsilon_{Ci}\tilde{Q}_i] = -M_i\sigma_{Ci}^2 \qquad \text{[A1.5]}$$

So taking expectations of [A1.1] by using [A1.2]-[A1.5] gives

$$A^P{}_i = V_i Mp^P - \tfrac{1}{2}W_i[(Mp^P)^2 + \Sigma_i M_i^2\sigma_{Ci}^2]$$

$$\quad - (1+\mu)\,\{[\tfrac{1}{2}M_i[(p^P)^2+\sigma_{Ci}^2] - M_i\sigma_{Ci}^2\} - \mu\phi X_i p^P\ ; \qquad \text{[A1.6]}$$

and summing gives expected total net benefit for using the tax:

$$A^P = VMp^P - \tfrac{1}{2}W[(Mp^P)^2 + \Sigma_i M_i^2\sigma_{Ci}^2] - \tfrac{1}{2}(1+\mu)[M(p^P)^2 - \Sigma_i M_i\sigma_{Ci}^2] - \mu\phi Xp^P,$$

which using $X = E^b - Mp^P$ from [3] and [A1.2] means

$$A^P = \bar{A}(p^P) + \tfrac{1}{2}\Sigma_i[(1+\mu)(1/M_i) - W]M_i^2\sigma_{Ci}^2, \text{ where} \qquad \text{[A1.7]}$$

$$\bar{A}(p^P) := VMp^P - \tfrac{1}{2}M(1+\mu+WM)(p^P)^2 - \phi\mu(E^b - Mp^P)p^P. \qquad \text{[A1.8]}$$

We find the optimal tax rate by setting $\partial A^P/\partial p^P = 0$:

$$\partial A^P/\partial p^P = VM - M(1+\mu+WM)p^P - \mu\phi E^b + 2\mu\phi M p^P$$

$$= M(V - \mu\phi E^b/M) - M[1+(1-2\phi)\mu+WM]p^P = 0; \quad \text{so optimally,}$$

$$p^P = (V-\mu\phi E^b/M) \,/\, [1+(1-2\phi)\mu+WM] \qquad =: p^* \qquad \text{as in [13]}$$

(which is invalid if $V-\mu\phi E^b/M < 0$, as discussed after [15]);

$$\bar{A}(p^*) = M(V-\mu\phi E^b/M)p^* - \tfrac{1}{2}Mp^*(V-\mu\phi E^b/M)$$

$$= \tfrac{1}{2}M(V-\mu\phi E^b/M)^2 \,/\, [1+(1-2\phi)\mu+WM] \qquad =: A^* \qquad \text{as in [11];}$$

$$\text{so } A^P = A^* + \tfrac{1}{2}\Sigma_i[(1+\mu)(1/M_i)-W]M_i^2\sigma_{Ci}^2, \qquad \text{as in [9].}$$

For *tradable permits*, where $\tilde{p} = \tilde{p}^T$, $\tilde{C}_i'(\tilde{Q}_i) = \tilde{p}^T$ and [5] give

$$(1/M_i)\tilde{Q}_i + \varepsilon_{Ci} = \tilde{p}^T$$

$$\Rightarrow \tilde{Q}_i = M_i\tilde{p}^T - M_i\varepsilon_{Ci}, \quad \tilde{Q} = M\tilde{p}^T - \Sigma_i M_i\varepsilon_{Ci}, \quad \text{and} \quad Q = Mp^T. \qquad \text{[A1.9]}$$

From [1] and [A1.9], total abatement $\tilde{Q}(\tilde{p}^T) = \tilde{E}^b - X$ is also:

$$\tilde{Q} = E^b - X + \tilde{E}^b - E^b = Mp^T + \Sigma_i E^b{}_i\varepsilon_{Ei}, \qquad \text{[A1.10]}$$

so using the mean and independence assumptions in [2],

$$\Rightarrow \mathrm{E}[\tilde{Q}^2] = (Mp^T)^2 + \Sigma_i(E^b{}_i)^2\sigma_{Ei}{}^2; \qquad \text{[A1.11]}$$

and [A1.9] and [A1.10] together give

$$M\tilde{p}^T - \Sigma_i M_i\varepsilon_{Ci} = Mp^T + \Sigma_i E^b{}_i\varepsilon_{Ei}$$

$$\Rightarrow \tilde{p}^T = p^T + (1/M)\Sigma_k(M_k\varepsilon_{Ck} + E^b{}_k\varepsilon_{Ek})$$

$$\Rightarrow \tilde{Q}_i = M_i[p^T + (1/M)\Sigma_k(M_k\varepsilon_{Ck} + E^b{}_k\varepsilon_{Ek}) - \varepsilon_{Ci}] \qquad \text{[A1.12]}$$

$$\Rightarrow \varepsilon_{Ci}\tilde{Q}_i = M_i[p^T + (1/M)\Sigma_k(M_k\varepsilon_{Ck} + E^b{}_k\varepsilon_{Ek}) - \varepsilon_{Ci}]\,\varepsilon_{Ci}$$

$$\Rightarrow \mathrm{E}[\varepsilon_{Ci}\tilde{Q}_i] = [(1/M)M_i^2 - M_i]\,\sigma_{Ci}{}^2 = (1/M - 1/M_i)\,M_i^2\sigma_{Ci}{}^2. \qquad \text{[A1.13]}$$

Also, from [A1.12],

$$\tilde{Q}_i^2 = M_i^2[p^T + (1/M)\Sigma_k(M_k\varepsilon_{Ck}+E^b_k\varepsilon_{Ek}) - \varepsilon_{Ci}]^2$$

$$= M_i^2\,\mathbf{[}(p^T)^2 + (1/M)^2[\Sigma_k(M_k\varepsilon_{Ck}+E^b_k\varepsilon_{Ek})]^2 + \varepsilon_{Ci}^2$$

$$+ 2p^T(1/M)\Sigma_k(M_k\varepsilon_{Ck}+E^b_k\varepsilon_{Ek}) - 2p^T\varepsilon_{Ci} - (2/M)\Sigma_k(M_k\varepsilon_{Ck}+E^b_k\varepsilon_{Ek})\varepsilon_{Ci}\mathbf{]}$$

$$\Rightarrow \mathrm{E}[\tilde{Q}_i^2]= M_i^2\,\mathbf{[}(p^T)^2 + (1/M)^2\Sigma_k[M_k^2\sigma_{Ck}^2+(E^b_k)^2\sigma_{Ek}^2] + \sigma_{Ci}^2 - (2/M)M_i\sigma_{Ci}^2\mathbf{]} \qquad [A1.14]$$

So taking E[$\tilde{A}^T_i$] from [A1.1], using [A1.11]-[A1.14] and E[$(\Sigma_i E^b_i\varepsilon_{Ei})^2$] = $(E^b_i)^2\sigma_{Ei}^2$ from [2], gives

$$A^T_i = V_iMp^T - \tfrac{1}{2}W_i\mathbf{[}(Mp^T)^2 + \Sigma_i(E^b_i)^2\sigma_{Ei}^2\mathbf{]}$$

$$- (1+\mu)\tfrac{1}{2}M_i\,\mathbf{[}(p^T)^2 + (1/M)^2(\Sigma_kM_k^2\sigma_{Ck}^2 + \Sigma_i(E^b_i)^2\sigma_{Ei}^2) + \sigma_{Ci}^2 - (2/M)M_i\sigma_{Ci}^2\mathbf{]}$$

$$- (1+\mu)(1/M - 1/M_i)M_i^2\sigma_{Ci}^2 - \phi\mu X_i p^T; \qquad [A1.15]$$

and summing then gives

$$A^T = VMp^T - \tfrac{1}{2}W\mathbf{[}(Mp^T)^2 + \Sigma_i(E^b_i)^2\sigma_{Ei}^2\mathbf{]}$$

$$- \tfrac{1}{2}(1+\mu)M\,\mathbf{[}(p^T)^2 + (1/M)^2(\Sigma_kM_k^2\sigma_{Ck}^2+\Sigma_i(E^b_i)^2\sigma_{Ei}^2)\mathbf{]}$$

$$- \tfrac{1}{2}(1+\mu)\Sigma_iM_i\sigma_{Ci}^2(1-2M_i/M)$$

$$- (1+\mu)\Sigma_i(1/M - 1/M_i)M_i^2\sigma_{Ci}^2 - \phi\mu Xp^T$$

which with $X = E^b - Mp^T$ from [3] and [A1.9] becomes

$$= VMp^T - \tfrac{1}{2}M(1+\mu+WM)(p^T)^2 - \phi\mu Xp^T$$

$$- \tfrac{1}{2}[(1+\mu)/M + W]\Sigma_i(E^b_i)^2\sigma_{Ei}^2 - (1+\mu)(\tfrac{1}{2}/M)\Sigma_iM_i^2\sigma_{Ci}^2$$

$$- (1+\mu)\Sigma_i(\tfrac{1}{2}/M_i - 1/M)M_i^2\sigma_{Ci}^2 - (1+\mu)\Sigma_i(1/M - 1/M_i)M_i^2\sigma_{Ci}^2 \qquad [A1.16]$$

So

$$A^T = \bar{A}(p^T) + \tfrac{1}{2}\Sigma_i[(1+\mu)/M_i-(1+\mu)/M]M_i^2\sigma_{Ci}^2 - \tfrac{1}{2}[(1+\mu)/M+W]\Sigma_i(E^b_i)^2\sigma_{Ei}^2,$$

where $\bar{A}(.)$ is as in [A1.8]. The same optimisation then applies, giving

$p^T = p^*$ as in [13] and $\bar{A}(p^T) = A^*$ as in [11].

Hence

$$A^T = A^* + ½Σ_i[(1+μ)/M_i−(1+μ)/M]M_i^2σ_{Ci}^2 − ½[(1+μ)/M+W]Σ_i(E^b_i)^2σ_{Ei}^2$$

as in [10].

II. WITH CORRELATIONS IN EMISSION UNCERTAINTIES

If $E[ε_{Ei}ε_{Ek}] = σ_{Eik} ≠ 0$ instead of = 0, then

$$E[(Σ_iE^b_iε_{Ei})^2] = Σ_i(E^b_i)^2σ_{Ei}^2 + 2Σ_{i≠k}E^b_iE^b_kσ_{Eik}$$

instead of just $Σ_i(E^b_i)^2σ_{Ei}^2$ as in [A1.11]. So in the working from [A1.14] onwards, and hence in the final result for the trading welfare A^T, all $Σ_i(E^b_i)^2σ_{Ei}^2$ terms are replaced by $Σ_i(E^b_i)^2σ_{Ei}^2 + 2Σ_{i≠k}E^b_iE^b_kσ_{Eik}$, as stated after [14]. (We still assume all $E[ε_{Ci}ε_{Ek}] = 0$, so that $E[ε_{Ci}\tilde{Q}_i]$ in [A1.13] is unchanged.)

By contrast, $ε_{Ei}$ makes no appearance in $\tilde{Q}_i$ for a tax, so $σ_{Eik}$ is absent from the tax welfare A^P.

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