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Complying with the Kyoto Protocol under uncertainty: Taxes or tradable permits? ☆

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ABSTRACT

The Kyoto Protocol allocates tradable emission allowances (AAUs) to developed countries, but they are free to choose a set of policy instruments to comply with these targets. We compare two different policy instruments: a tax and purely domestic tradable permits, for the European Union, the US and Japan. Information on abatement costs and international permit price is imperfect and stems from nine global economic models. For a country party to the Protocol, the benefit of emission reduction is that it can sell more or has to buy less AAUs. We show that in this context, permits entail a slightly lower expected cost than a tax for the US and Japan, whereas both instruments yield an almost equal outcome for Europe. Applying Weitzman's framework (Prices vs. quantities, RES, 1974) in this context, we show the importance of the positive correlation between costs and benefits: technology shocks that lead to low abatement costs in one country generally lead to low abatement costs in other countries too, thereby leading to a low international permit price in the true-up period.

1. Introduction

Countries face a decision of how to domestically implement greenhouse gas control policy to achieve emissions targets to which they have agreed under the Kyoto Protocol, or to which they may agree under the next international agreement(s) on climate change. The Protocol includes various mechanisms that allow for international exchange of credits, but countries are free to choose the mechanisms by which they achieve their domestic target. In particular, even though the Protocol includes national quantitative targets, a country may choose to use a price mechanism, i.e. a carbon tax, to achieve the target. Indeed, many European countries have implemented or are implementing, a carbon tax: Norway, Sweden, Ireland, etc. Given the uncertainty in the level of emissions a given carbon tax will lead to, there is uncertainty on whether a country using a price mechanism will indeed achieve its agreed target. A given tax rate might lead to greater than expected reductions, and the country would then have excess credits at the end of Kyoto's first commitment period. Alternatively, it may lead to emission levels above the targets in which case the country would need to reconcile its accounts to meet its commitments. The Marrakech Accords anticipate such a possibility by including an "additional period for fulfilling commitments", also known as a "true-up" period where countries may obtain credits from abroad or negotiate the sale of excess credits. Afterwards, countries may also bank credits against future reductions, or essentially (through the non-compliance provisions) borrow against the future by adding reductions to future commitments at a 5% annual interest rate. On the other hand, a quantity mechanism will achieve the target level with certainty but the country faces uncertainty in the cost of achieving this reduction. The cost may be greater or less than the going price of credits in a true-up period.[1]

This issue raises the familiar problem of the choice between a price and a quantity mechanism under uncertainty (Weitzman, 1974). Here, the benefits of price versus quantity mechanisms is purely in terms of the value of permits available to sell in the true-up period or the avoided cost of acquiring permits to cover a missed target.

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[1] Many observers seem to believe that the Kyoto Protocol to the U.N. Framework Convention on Climate Change requires its parties to cover their firms by internationally tradable permits. This is doubly false. The Protocol allocates tradable quantitative emission limits to States, but they are free to choose the means to respect this quota: purchase of international permits and credits, command-and-control regulations, implementation of a domestic tradable permit system, carbon taxes, etc. Furthermore, even if a party chooses to set a domestic tradable permit system, nothing requires that these permits should be exchangeable with other party's tradable permit schemes, or with Kyoto's permits and credits.

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Several papers, e.g. by Pizer (1999), applied Weitzman's framework to discriminate between a price instrument (taxes) and a quantity one (quotas) as the basis for an international agreement for climate protection. They demonstrated that a price instrument is preferred as an international mechanism to tackle climate change.

In the present paper, we show that Weitzman's analysis may also be applied to climate change in a different context: the choice of an instrument by a country which has ratified the Kyoto Protocol and wants to comply with this agreement. We stress that this question is entirely different from the one dealt with by Pizer (1999), hence our conclusions do not challenge these well-established results. Pizer et al. evaluate instruments based on their ability to maximize expected net benefits whereas this paper focuses on minimizing expected costs subject to an emissions target combined with international flexibility. This is a cost effectiveness exercise, not a welfare maximization problem.

In this context, the benefit from abating one extra ton of CO_2 is that this country will be able to buy one less or sell one more assigned amount units (AAUs, the international permits created by the Kyoto Protocol). The ideal policy, i.e. the one that would always bring the ex post optimum, would be to set a tax equal to the ex post AAU price. Of course, this price cannot be known with certainty ex ante, since it will be influenced by business-as-usual emissions and by the cost of emission reduction options.

Guesnerie (2010) concludes that in such a situation, a country should implement a tax (whose rate should be set at the expected permit price), rather than a system of tradable permits. Indeed, for a country price-taker on the permits market, the marginal benefits curve is flat, hence, in the basic Weitzman's framework, a price instrument brings a higher benefit than a quantity instrument. The argument is sound but as we will see, in a more complex framework, there is also a good argument in favour a quantity instrument, i.e. a tradable permits market: costs and benefits are likely to be positively correlated which, in Weitzman's framework, favours the quantity instrument over the price instrument.

In the present paper, we assess the expected outcome of a price instrument (a tax), a quantity one (non-internationally exchangeable tradable permits), and, as a benchmark, a virtual "ideal" instrument that would guarantee the realisation of the ex post optimum, as analysed by Ireland (1977). We provide this analysis for three countries/regions: the European Union, Japan and the US. Our main starting point is that the benefit from reducing emissions is not measured in environmental terms because, as a first approximation, the global emission cap (among developed countries) is fixed by Kyoto. Instead, the benefit from domestic emission abatement is in terms of international permits sold, banked or not bought by the government at the end of Kyoto's first commitment period (2008–2012). That is, we are interested in the choice of price versus quantity mechanisms purely in terms of the cost-effectiveness of complying with the Protocol rather than the broader issue of the costs and benefits of climate change mitigation itself.

We proceed as follows. In the second section, we present our assumptions in more depth. We then compare the expected net benefit of the price, quantity and "ideal" instruments, on the basis of the non-linear reconstructed marginal cost curves of the nine models (Section 3). It turns out that in the US and Japan, permits perform better than taxes and that the outcome of the two policy instruments in very close in the EU. This contradicts the basic version of Weitzman's model, which would conclude in favour of the tax, due to the flatness of the benefit curve. We thus explain our results by applying various expanded versions of this model, using local linear approximations of our marginal abatement cost curves (Section 4). The crucial factor is the positive correlation between costs and benefits, which stems from the fact that, except for Europe, models which predict a low abatement cost curve also forecast a low international permit price. Section 5 concludes.

2. Assumptions

2.1. Definition of benefits

As we already stated, the benefit from reducing domestic emissions is not measured in environmental terms but in term of international permits (Kyoto AAUs) that can be sold, banked or that do not have to be bought or de facto borrowed. This may puzzle an environmental economist, but, after all, Weitzman's framework was not specifically developed for environmental purposes. The rationale for our interpretation is that the global emission cap (among developed countries) is fixed by the Kyoto Protocol. As a consequence, and disregarding the various loopholes in the Kyoto and Marrakech agreements, every extra abatement in one country corresponds to less international permits import (or more export), so it implies less abatement abroad. International permits may also be banked for future commitment periods, but then again, if future commitment periods are defined soon enough and if expectations are correct, the present marginal benefit from banking them is their current price (Helioui, 2002).

2.2. Information on costs and benefits

All the information available on abatement costs and permit price (hence marginal benefits from abatement) is taken from nine global models: AIM, MIT-EPPA, G-cubed, Abare-GTEM, MERGE3, MS-MRT, the Oxford Model, RICE and SGM. We consider only uncertainty across models and disregard the uncertainty within each model. In other words, the authority in each group of country knows that all these models are highly imperfect, but it has no other information source and places the same subjective probability of realisation on each model.[2]

We construct proxies of these models' marginal abatement cost curves by a procedure similar to Weyant and Hill (1999) and Hourcade and Ghersi (2002). The 16th Energy Modelling Forum study (hereafter EMF 16) provides, for each of these models, a marginal abatement cost for three configurations of compliance to the Kyoto Protocol: global trade in international permits, trade limited to Annex I countries, no trade.[3] Together with the requirement that zero abatement entails zero abatement cost, this provides us with four (price, quantity) pairs for each model. We then compute least-squares fits to these data as linear combinations of x, x^2 and x^3, x being the abatement

[2] Of course, the authority may also trust some models more than others, and models are not independent since many of them are based on the same datasets, functional forms and economic theories. As a consequence, there is a case for using a more complex weighing method than simple average in the expected cost calculation. For example, more weights could be given to models which have the best performance in replicating past economic trends, and to models based on original datasets, functional forms and economic theories. Such procedures are increasingly used for climate model ensembles (see e.g. Tebaldi and Knutti, 2007).We do not have the data for implementing such a complex procedure here, but as a first step in this direction, we tested the robustness of our main results by dropping in turn each model from the model ensemble (cf. footnote 7 in Section 3 below).

[3] These data are rather old, but unfortunately no other systematic multi-model ensemble exists with more recent simulations. Four other models are included in the EMF study but we have not taken them into account because of a lack of data availability.

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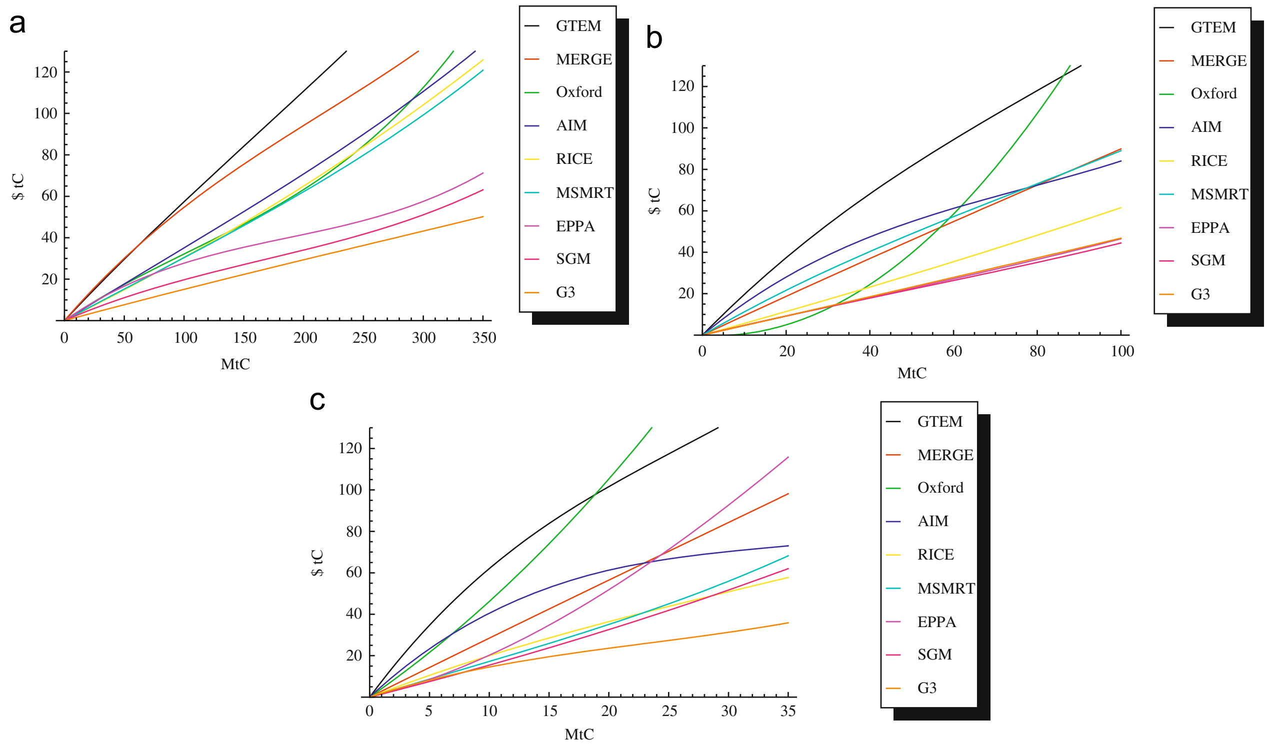

Fig. 1. Reconstructed marginal abatement cost and benefits curves for each model. (a) United States, (b) Europe and (c) Japan.

(cf. Appendix A).[4] Every curve thus matches every equilibrium computed by the models and available to us.[5] Fig. 1 below displays these fitted functions for each region and each model.

This procedure is open to some criticisms. First, assuming a domestic marginal abatement cost in one country, independently of what the other countries do, neglects activity relocation driven by international trade in the goods market (Copeland and Taylor, 2000), terms of trade effects and hydrocarbon price feedbacks. Second, most models we use do not include other gases than CO_2, carbon sequestration and local ancillary benefits from emission reductions (in particular the decrease in air pollution). As a consequence, they overestimate both costs and benefits.[6] Last, they assume US participation in the Protocol. However, to date, no systematic comparison of models that includes these features is available.

We provide results on three world regions: Europe, the US and Japan. Weyant and Hill (1999) also present results for a fourth region, CANZ (Canada, Australia and New-Zealand), but since there is no political coordination between these three countries, providing policy recommendations for this whole region would be of little interest.

2.3. Market power in the international permit market

We assume that each country is a price-taker in the international permit market, not for the reason that market power is unlikely, but because the simulations reported in Weyant and Hill (1999) do so. However, we will see in the conclusion that accounting for market power would increase the advantage of permits over taxes.

2.4. Availability of information

As in Weitzman's model, when we examine the tax and the non-internationally exchangeable tradable permits, we presume that firms know the true abatement cost curve when they make their productive decisions, while the government has only limited information on this curve. Since our model is not dynamic, the government cannot adjust its policy. At the end of Kyoto's first commitment period, when emissions and international permit price are known, each country buys the international permits required to comply with its commitment (if any), or banks or sells excess permits, or de facto borrows permits to cover excess emissions. Such trades may take place during the "additional period for fulfilling commitments" (also known as the "true-up period"), established for this purpose by the Marrakech Accords, which will last one hundred days after the approval of national emission inventories for year 2012.

We do not require that the international permit market clears at the end of the first commitment period. Since the ex post equilibrium will in general differ from what is expected, our three countries/

[4] All computations have been done with Wolfram Mathematica. Mathematica notebooks are available from the author upon request.

[5] The only computational problem aroused for the Oxford model applied to Europe: the curve fitted with the usual procedure exhibited a huge negative cost for limited abatement levels. We thus used a linear combination of only x and x^2 in this case.

[6] Concerning marginal benefits, we choose the set of prices corresponding to the EMF "global trade" scenario rather than those corresponding to the EMF "trade limited to Annex I countries" scenario. Admittedly, the Kyoto Protocol does not allow for permit trade with developing countries, apart through the Clean Development Mechanism, so the second scenario might appear more relevant. However, the set of international permit prices in the second scenario is much higher than more recent forecasts. Indeed, the models used in the EMF study over-estimate the international permit price because of the various factors not included in the modelling exercises and mentioned above: sinks, other gases and revision of baselines. As a consequence, the price ranges corresponding to a global market in the EMF 16 study is much more likely than the one corresponding to an Annex I market.

regions as a whole will in general hold more or less permits than needed to cover their emissions. This assumption is consistent with the Kyoto system, which allows banking and de facto borrowing (through its compliance system agreed in Marrakech).

The ideal price instrument, presented as a benchmark to assess the supplementary cost of uncertainty, further assumes that firms know the international permits price when they make their productive decisions. To go further would require dynamic abatement cost curves, to take into account inertia in emissions.

2.5. Risk neutrality

As in most of post-Weitzman literature, we assume away risk-aversion and simply suppose that the government minimises the expected cost of compliance for each instrument.

3. Simulations

For each country/region, we first choose the quantity that minimises the expected net cost from a given abatement $\hat{q}$:

$$ECQ(\hat{q}) \equiv \frac{1}{9}\sum_{i=1}^{9}\left(\int_0^{\hat{q}} MAC_i(x)dx + p_i^*(BaU_i - \hat{q} - K_i)\right) \quad (1)$$

where $\hat{q}$ is the abatement, $i \in \{1,9\}$ represents a model, $MAC_i\,(x)$ is the marginal cost for an absolute abatement x, p_i^* is the international permit price, BaU_i is business-as-usual emissions and K_i is the Kyoto target, all according to model i. This function is a polynomial of degree 4 but it admits a unique minimum for each of our three world regions. Fig. 2 presents the resulting graphs (note that throughout the text, "billion" means 10^9).

The expected compliance cost from a tax is, for a given tax rate $\tilde{p}$:

$$ECP(\tilde{p}) \equiv \frac{1}{9}\sum_{i=1}^{9}\left(\int_0^{h_i(\tilde{p})} MAC_i(x)\,dx + p_i^*(BaU_i - h_i(\tilde{p}) - K_i)\right) \quad (2)$$

where $h_i(\tilde{p})$ is the abatement in response to the tax, computed by equalizing the marginal abatement cost to the tax level, for each model i.

This function also admits a unique minimum for each country/region. Fig. 3 presents the resulting graphs.

We then compute the relative advantage of the optimal tax over permits in optimal quantity, i.e., Weitzman's delta (Table 1). For each region, the cost difference between the optimal tax and the optimal permit scheme is very low: between −0.2% and 1.6% of the cost of the permit scheme.[7]

Table 1 presents a puzzle since it suggests that the instruments perform equally well. But why do not taxes outperform permits as Weitzman's basic model suggests they should, since our benefit curve is flat? As the next section demonstrates, this result can be explained by more sophisticated versions of this framework.

Before, as a benchmark, it is useful to compute the expected cost of an ideal instrument, i.e., which always matches the ex post optimum:

$$ECII \equiv \frac{1}{9}\sum_{i=1}^{9}\left(\int_0^{q_i^*} MAC_i(x)\,dx + p_i^*(BaU_i - q_i^* - K_i)\right) \quad (3)$$

where q_i^* is the abatement predicted by model i in the "global permit trade" scenario of the EMF. Results are presented in the last column of Table 1. Obviously, the costs of both instruments are higher than that of the ideal instrument, although the maximum incremental cost remains limited: +10% for the tax in the US compared to the ideal instrument.

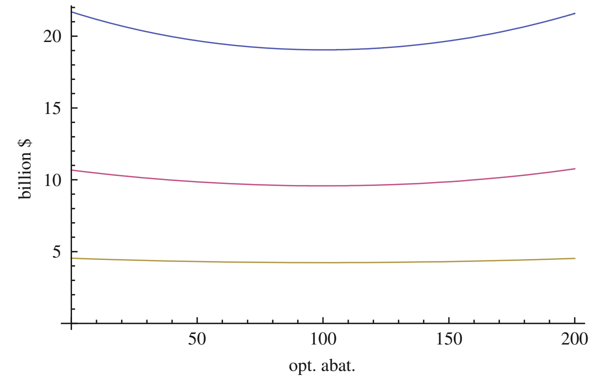

Fig. 2. Net expected cost from a given abatement, in % of the optimal abatement. Top curve: United States; middle curve: Europe; bottom curve: Japan.

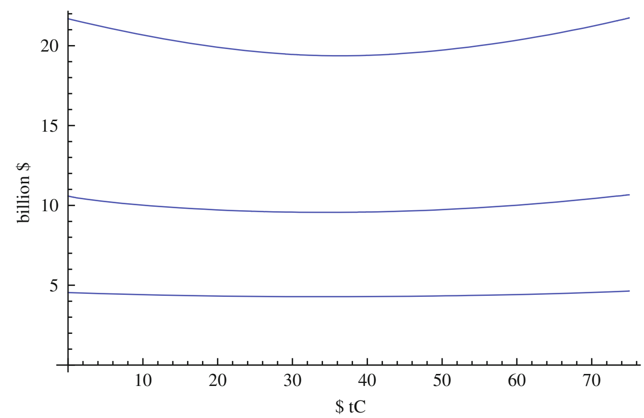

Fig. 3. Net expected cost from a given tax. Top curve: United States; middle curve: Europe; bottom curve: Japan.

4. Explaining our results through a literature review

The formal economic analysis of the choice between a price instrument (i.e., a tax) and a quantity instrument (i.e., a tradable permit scheme) for protecting the environment dates back to Weitzman's 1974 seminal paper. The author first recalls that, as long as the abatement cost curve is known with certainty, both instruments are equivalent. However, in case of uncertainty on abatement costs, this is no longer the case. To go further, he used local linear marginal abatement costs and benefits, approximated around the optimum.

4.1. Weitzman's simplest model

In the simplest model of Weitzman's paper, the marginal abatement cost is[8]

$$C_q(q,\alpha) = c_1 + \alpha + c_2(q - \hat{q})$$

where q is the abatement, $\hat{q}$ is the optimum, c_1 and c_2 are strictly positive parameters and α is a random variable standardised so that $E[\alpha]=0$. Note that α represents the uncertainty over both the

[7] To check the robustness of these results, we performed the same computation nine times more, each time dropping one of the models hence working on an eight-model ensemble. For the US, the expected advantage of permits over the tax ranges from 0.4% to 3.5% of the cost of permits, depending on what model is dropped out. Hence our conclusion of a rough equality or a slight superiority of permits over taxes in this context remains valid.

[8] For the sake of clarity we slightly modify Weitzman's notations by using c_1 instead of C', c_2 instead of C'', b_1 instead of B' and b_2 instead of $-B''$.

Table 1
Optimal level and outcome of our three instruments.

	Optimal tax		Optimal permit scheme		Expected advantage of permits over the tax, in % of the cost of permits	Expected cost of the ideal instrument (bn $)
	Rate (US $_{1990}$/t C)	Expected cost (bn $)	Expected abatement (MtC)	Expected cost (bn $)		
US	36.5	19.37	130	19.05	1.6%	17.61
Europe	34.5	9.56	52	9.58	−0.2%	9.11
Japan	33.5	4.28	15	4.23	1.1%	4.12

cost of abatement options and the level of business-as-usual emissions: for a given cost of abatement options, a higher level of production, hence of business-as-usual emissions, would entail a higher α, and so would a higher cost of abatement options. Quirion (2005) develops this point further. In our model ensemble, however, models diverge a lot about the cost of abatement options (Fig. 1) but forecast rather similar business-as-usual emissions (Table A1, first column). Note also that, as stressed by Ireland (1977; p. 185), this literature provides no clue on how to choose the optimum $\hat{q}$. The marginal abatement benefit is

$$B_q(q,\beta) = b_1 + \beta - b_2(q - \hat{q})$$

where b_1 and b_2 are strictly positive parameters[9] and β is a random element standardised so that $E[\beta]=0$. An additional assumption (relaxed later) is that α and β are uncorrelated.

The author then derives the reaction function $h(p)$ by which firms react to a tax p, the optimal tax rate $\tilde{p}$ and the comparative advantage of taxes over permits:

$$\Delta_1 \equiv E\left[B(h(\tilde{p})) - C(h(\tilde{p}))\right] - E\left[B(\hat{q}) - C(\hat{q})\right] = \frac{\sigma^2}{2{c_2}^2}(c_2 - b_2)$$

where σ^2 is the variance of α.

One can see that Δ_1 is positive, i.e., a tax should be preferred, if and only if the marginal abatement cost curve is steeper than the marginal environmental benefit curve ($c_2 > b_2$). In our context, because the marginal benefit curve is completely flat ($b_2=0$), Δ_1 is always positive.

However, two footnotes in Weitzman's article, developed further in the subsequent literature, draw a more complex picture.

4.2. *Uncertainty on the slopes of the marginal abatement cost and benefits curves*

First, there may be an uncertainty on the slopes, not only on the positions, of the marginal abatement cost and benefit curves:

$$C_q(q,\alpha,f) = c_1 + \alpha + \frac{c_2}{f}(q - \hat{q}) \tag{4}$$

$$B_q(q,\beta,g) = b_1 + \beta - \frac{b_2}{g}(q - \hat{q}) \tag{5}$$

where f and g are random variables standardised so that $E[f]=E[g]=1$. Weitzman further assumes that all random variables are uncorrelated.

The comparative advantage of taxes over permits is now:

$$\Delta_2 = \frac{\sigma^2}{2{c_2}^2}(c_2 - (1+\delta^2)b_2)$$

[9] All results below remain valid for a downward-sloping marginal benefit curve (b_2 negative) as long as we have $c_2 > -b_2$ to avoid a corner solution, i.e., a complete abatement.

where δ^2 is the variance of f. A higher variance generally favours permits over prices, but has no effect in our situation, since we have $b_2=0$.

4.3. *Correlation of the uncertainty on costs and on benefits*

If there is a correlation between α and β (but not between the other random variables), we have

$$\Delta_3 = \frac{\sigma^2}{2{c_2}^2}\left(\left(1 - 2\frac{\sigma_{BC}}{\sigma^2}\right)c_2 - b_2\right)$$

and with, in addition, uncertainty on the slopes of the two curves:

$$\Delta_4 = \frac{\sigma^2}{2{c_2}^2}\left(\left(1 - 2\frac{\sigma_{BC}}{\sigma^2}\right)c_2 - (1+\delta^2)b_2\right)$$

where σ_{BC} is the covariance of α and β. A positive (negative) covariance reduces (increases) the advantage of taxes over permits. Computations by Stavins (1996) suggest that this covariance is more likely to switch the choice from taxes to permits than the other way round. In our context where $b_2=0$ and $c_2>0$, the tax is preferred if the correlation between costs and benefits is positive and high enough compared to the variance of the cost, more precisely if and only if

$$\sigma_{BC} > \frac{\sigma^2}{2} \tag{6}$$

4.4. *Other correlations*

With other correlations between the random variables, it becomes very difficult to get clear-cut results. Yohe (1977) graphically studies the effect of the correlation of α and f, neglecting any other correlation. It turns out that a negative (positive) correlation of α and f, i.e., a steeper (flatter) marginal cost curve usually associated with a higher position of this curve, favours permits (taxes). Analytically, the comparative advantage of taxes over permits is now rather complex, even if we assume away the uncertainty on the slope of the benefit curve:

$$\Delta_5 = E\left[\frac{f\alpha^2}{2c_2} + \frac{{b_2}^2 f^2 \alpha\sigma_{f\alpha}}{{c_2}^2(b_2+c_2)} + \frac{b_2 f\beta\sigma_{f\alpha}}{c_2(b_2+c_2)} - \frac{b_2 f^2\alpha^2}{2{c_2}^2} - \frac{f\alpha\beta}{c_2}\right] - \frac{{b_2}^2(c_2 + b_2(1+\delta)^2){\sigma_{f\alpha}}^2}{2{c_2}^2(b_2+c_2)^2}$$

In our context, with $b_2=0$, we end up with a much simpler expression:

$$\Delta_6 = E\left[\frac{f\alpha^2}{2c_2} - \frac{f\alpha\beta}{c_2}\right]$$

The first, positive, term reflects the relative slope effect as in Section 4.1 and the second, which may be positive or negative, the correlation between costs and benefits as in Section 4.3. However, note that both terms are modified by correlations with the slope of the cost curve.

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Table 2
Approximations of the comparative advantage of taxes over permits.

(million US $_{90}$)	Simulations from Section 3, with the non-linear MACCs	Linear approximations		
		No correlation cost–benefit ($\Delta_1=\Delta_2$)	Correlation cost–benefit ($\Delta_3=\Delta_4$)	Correlations cost–benefit-slope ($\Delta_5=\Delta_6$)
US	−319	624	−132	−402
Europe	15	278	209	−14
Japan	−51	124	−72	−60

4.5. *Why do not taxes perform better than permits?*

Which of the above mentioned mechanisms is able to explain the results presented in Section 3? To cast some light on this question, we have computed linear marginal cost and benefit curves around the optimum, chosen as the mean abatement in the EMF "global trade" scenario.[10] We have then computed the parameters and random variables for Eqs. (4) and (5) above.

Table 2 below presents the comparative advantage of taxes over permits based on simulations from Section 3, with the non-linear MACCs, and the various linear approximations that we have surveyed in Sections 4.1–4.4.

The standard formula Δ_1 (which is equal to Δ_2 with our flat benefit curve) which only accounts for the relative slopes naturally concludes to an overwhelming domination of the price instrument and is thus a very bad indicator in our context. Δ_3 (which is equal to Δ_4 with our flat benefit curve) always invites to use the instrument which (in the simulations from Section 3) presents the lowest expected cost, although for the US and Europe it is significantly biased towards the price instrument. Last, Δ_5 (equal to Δ_6 with our flat benefit curve) which takes into account all the relevant correlations, gets closer to the Δcomputed with the non-linear MACCs in Section 3 than Δ_3 for the US and Europe, but not for Japan. The remaining divergence with the Δ computed with the non-linear MACCs in Section 3 is due to the non-linearity of the marginal cost curves.

Overall, it turns out that the dominant effect is by far the correlation between costs and benefits, which is positive for all three regions, but lower for Europe than for the others: the correlation coefficients between α and β are 0.29 for the US, 0.07 for Europe and 0.48 for Japan. In Europe, the correlation is too low to overcome the other force driving the results in the opposite direction, i.e. the relative slope of the marginal cost and benefit curve. Unfortunately, there is no way to explain why the abatement cost curves in Europe are less correlated to the international permits price than those in the US and in Japan.

The explanation of the positive correlation between costs and benefits is the following: models that are "optimistic", i.e., that predict a relatively low abatement cost curve, in one country, generally do so in other world regions too, thereby forecasting a relatively low international permit price. Indeed, if, say, hybrid cars, wind generators or clean substitutes to fluorinated gases are cheaper than expected at the end of this decade in the US, the same will happen in other world regions, thus reducing the international permit price. Likewise, if business-as-usual emissions are lower than expected in the US, this will much likely be driven by a lower than expected GDP growth; given the degree of economic globalization, it is likely than GDP will also be lower than expected in other world regions.

[10] cf. Appendix A. This is not the true optimum quantity, as computed in the last section, because the genuine cost curves are not linear but third degrees polynomials. However, these optimums differ only by a few percents.

The influence of the positive correlation of benefits and costs is often seen as an interesting but rather academic possibility. In our context, however, it is of the utmost importance.

Last, the correlation between the slope of the marginal cost curve and the position of the benefit cost curve has not been mentioned anywhere in the literature, to our knowledge. However it is quantitatively important in our context, for the US and especially for Europe: compare Δ_5–Δ_3 in Table 2 above.

5. Conclusions

Although Weitzman's framework for choosing an instrument under uncertainty has been applied by several authors to the choice of an international coordination regime against climate change, it had never been used to choose a domestic instrument for complying with the existing international climate change mitigation regime—the Kyoto Protocol. In this context, the benefits from reducing emissions are in terms of international emission permits (AAUs) rather than in terms of reduced climate change.

Using nine global economic models as the source of information and uncertainty on abatement cost curves and international permit price, this paper provides the first such analysis.

According to our simulations, a quantity instrument performs a little better than a price one for complying with the Kyoto Protocol in the US and Japan, but the difference in expected cost is very low: less than 2%. Both instruments yield an almost equal expected cost in Europe. Hence our conclusions invite to base the choice between taxes and permits on other reasons than their robustness to uncertainty. Indeed, there are many other reasons, not captured in our framework, for choosing an instrument: ability to drive innovation, institutional constraints, political feasibility and so on.

In addition, we identify the main mechanism driving our results: the positive correlation between costs and benefits. The explanation is the following: models that are "optimistic", i.e., that predict a relatively low abatement cost curve, in one country, generally do so in other world regions too, thereby forecasting a relatively low international permit price. This positive correlation favours tradable permits over taxes, counteracting the fact that the slope of marginal benefits is lower than that of marginal cost, which favours taxes over tradable permits. In the future, this work could be extended in at least four directions.

First, more recent simulations, taking into account *inter alia* emission commitments beyond 2013, could be used if a systematic comparison in the spirit of Weyant and Hill (1999) were available.

Second, we have assumed no market power in the permit market, to stick with the assumptions of the simulations we use. Note that a country having a monopsony power in the international permit market would face a decreasing benefit curve, as more abatement would decrease the equilibrium price. From the standard Weitzman model, this would reinforce the advantage of the quantity over the price instrument, at least if some of the

Table A1
Abatement and carbon price for each model and scenario (US).
Source: Weyant and Hill (1999).

Model (BaU emissions, MtC)		Global trade	Annex I trade	No trade
AIM (1655.4)	Abatement (MtC)	107	184	390
	Carbon price ($/tC)	38	65	153
MIT-EPPA (1763.1)	Abatement (MtC)	91	364	534
	Carbon price ($/tC)	26	76	193
G-Cubed (1768.1)	Abatement (MtC)	131	372	526
	Carbon price ($/tC)	20	53	76
ABARE-GTEM (1719.3)	Abatement (MtC)	39	192	513
	Carbon price ($/tC)	23	106	322
MERGE3 (1733.6)	Abatement (MtC)	179	309	512
	Carbon price ($/tC)	86	135	264
MS-MRT (1785.8)	Abatement (MtC)	88	242	547
	Carbon price ($/tC)	27	77	236
Oxford (1770.6)	Abatement (MtC)	316	421	536
	Carbon price ($/tC)	123	224	410
RICE (1612.5)	Abatement (MtC)	61	191	364
	Carbon price ($/tC)	18	62	132
SGM (1822.3)	Abatement (MtC)	118	415	586
	Carbon price ($/tC)	22	84	188

correlations neglected by this model do not pull in a different direction. Other instruments could then perform better than the two single-value instruments we have looked at (the tax and the non-internationally exchangeable permits): a combination of permits, tax and subsidy, in the spirit of Roberts and Spence (1976) and a non-linear price instrument. However, since costs and benefits are positively correlated, the quantity instrument may then again perform better than these non-linear instruments (Shrestha, 2001).

Third, simulations displaying the cost of delaying abatement would allow us to test a potential advantage of internationally tradable permits over other instruments. Indeed if economic agents could wait for the true international permit price to be known before making their productive decisions, internationally tradable permits would perform as well as the contingent price instrument studied above. But obviously, since most greenhouse gases abatement decisions suffer from an important inertia, a delay in abatement would raise the abatement cost curve. However, *some* delay until new information arrives, especially in the most flexible sectors, may be beneficial.

Last, we could drop the assumption of risk-neutrality and use decision criteria that assume some degree of risk-aversion.

Appendix A. Computation of results presented in Sections 3 and 4.5

In this appendix, we present the procedure followed to produce the quantitative estimates. Since the procedure is identical for each country/region, we illustrate it with US data only. Data for Europe and Japan are available from the author upon request.

A.1. Generation of Fig. 1 and {MAC$_i$}

We approximate the MAC curve for each model and each country/region with a third degree polynomial, fitted using ordinary least squares. From the EMF 16 study, we get three (carbon price/abatement) pairs, each corresponding to a standardised scenario (global permit trade, permit trade restricted to Annex I, no permit trade). The requirement that zero abatement entails zero cost provides a fourth point. Table A1 above presents these data for the US.

Table A2
Stochastic parameters for the linear approximations (US).

Model	α_i	β_i	f_i
AIM	2.7	−5.0	0.7
MIT-EPPA	−9.3	−16.6	1.6
G-cubed	−22.5	−23.0	1.7
ABARE-GTEM	29.8	−19.4	0.5
MERGE3	24.4	43.9	0.6
MS-MRT	−3.1	−15.9	0.8
Oxford	−1.9	80.4	0.8
RICE	−2.4	−24.4	0.7
SGM	−17.7	−20	1.7

A.2. Generation of Table 1

The expected cost for a given abatement *ECQ* is then computed analytically according to Eq. (1). The Kyoto targets $\{K_i\}$ equal by definition the abatement required in the EMF "no trade" scenario (cf. Table 1), the $\{p_i\}$ are the carbon prices in the "global trade" scenario and the $\{BaU_i\}$ are indicated between brackets in Table 1.[11] For the US, we get:

$$ECQ = 21686.3 - 42.5538q + 0.191005q^2 - 0.000196121q^3 + 3.30968 \times 10^{-7} q^4$$

The expected cost for a given tax *ECP* is computed numerically for each country/region as follows. For each tax rate and each model i, the abatement level $h_i(\tilde{p})$ is computed by equalising MAC_i to this tax rate. *ECP* is then computed as indicated by Eq. (2).

At last, the expected cost from an ideal instrument *ECII* is computed for each country/region as indicated by Eq. (3). In substance, we average over the nine models the abatement corresponding to the international permit price forecasted by this particular model.

A.3. Generation of Table 2

For each model and country/region, we first compute the derivative of the MAC curve around an optimum, exogenously chosen as the abatement level in the EMF global trade scenario, averaged

[11] If all emissions covered by Kyoto were modelled, the difference $BaU_i - K_i$ would equal for each model i the emission target agreed under Kyoto. This is not the case because not all emissions and sinks are modelled.

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over the nine models. We then compute c_2 and $\{f_i\}$ so that, first, the slope for model i equals c_2/f_i and, second, the mean of $\{f_i\}$ equals 1.

To get the $\{\alpha_i\}$, we compute the $\{MAC_i\}$ at the above-mentioned optimum and shift the resulting vector so that the mean is zero.

Since $b_2=0$, to get the $\{\beta_i\}$ we just shift the $\{p_i\}$ so that the mean of the result is zero.

The resulting stochastic parameters for the US are presented in Table A2 above. The other parameters of Eqs. (1) and (2) are $c_1=b_1=42.6$, $c_2=0.24$, $b_2=0$.

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