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Second-best instruments for near-term climate policy: Intensity targets vs. the safety valve

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ABSTRACT

Current proposals for greenhouse gas emissions regulations in the United States mainly take the form of emissions caps with tradable permits. Since Weitzman's (1974) [3] study of prices vs. quantities, economic theory predicts that a price instrument is superior under uncertainty in the case of stock pollutants. Given the general belief in the political infeasibility of a carbon tax in the US, there has been recent interest in two other policy instrument designs: hybrid policies and intensity targets. We extend the Weitzman model to derive an analytical expression for the expected net benefits of a hybrid instrument under uncertainty. We compare this expression to one developed by Newell and Pizer (2006) [6] for an intensity target, and show the theoretical minimum correlation between GDP and emissions required for an intensity target to be preferred over a hybrid. In general, we show that unrealistically high correlations are required for the intensity target to be preferred to a hybrid, making a hybrid a more practical instrument in practice. We test the predictions by performing Monte Carlo simulation on a computable general equilibrium model of the US economy. The results are similar, and we show with the numerical model that when marginal abatement costs are non-linear, an even higher correlation is required for an intensity target to be preferred over a safety valve.

1. Introduction

As many countries prepare to begin their implementation of their pledges under the Copenhagen 2009 accord, and the United States begins more serious discussions of domestic climate policy [1] and potential future international frameworks [2], interest in alternative regulatory instruments for greenhouse gas emissions is increasing. Because greenhouse gases are stock pollutants, we expect their marginal benefits for a given decision period (1–5 years) to have a negligible slope. The seminal work by Weitzman [3,4] and extended by Pizer [5] and Newell and Pizer [6] showed that under cost uncertainty and relatively flat marginal damages that a carbon tax equal to the expected marginal benefit is superior to the optimal emissions cap.

Given the experience with an attempt at a BTU tax under the Clinton Administration, the prevailing view is that a carbon tax is politically infeasible, at least in the United States [6,28]. This political constraint on instrument choice, combined with the significant uncertainty in abatement costs under a pure quantity instrument, has generated interest in two suboptimal instruments that may be superior to quantity instruments in the presence of uncertainty: a hybrid or

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safety valve instrument, and an indexed cap or intensity target. The safety valve is one in which an emissions cap is set with tradable permits allocated, but if the permit price exceeds some pre-established trigger price, an unlimited number of permits are auctioned off at the trigger price [5,7,8], thus reverting to a carbon tax. An indexed cap is one in which the quantity of permits allocated is set not to an absolute emissions target, but rather is determined relative to some other measurable quantity, for example GDP, which is correlated with emissions [6,9,10]. A third alternative for improving a quantity instrument is to allow banking and borrowing over time [11,12]; in this paper, we restrict our analysis to a single period and focus on the hybrid and intensity target instruments.

Weitzman [3] originally developed an expression for the relative advantage of prices versus quantity instruments for a pollution externality in the presence of uncertainty. Pizer [5] showed that the safety valve for a stock externality under uncertainty is superior to a pure quantity instrument and as good as or better than a pure price instrument. Studies of an indexed cap or intensity target under uncertainty (e.g., [6,10,13]) have shown the advantage to be a function of the correlation between emissions and the indexed quantity, as well as the relative slopes of marginal costs and benefits, and the variance of the uncertainty. However, there have been no direct comparisons in the literature between indexed caps and hybrid instruments. Since this choice between second-best instruments is one key element in the current debate [1], it is useful to demonstrate both theoretically and empirically when indexed caps should be preferred to hybrid instruments or the reverse.

We briefly preview the intuition behind the key results here. A hybrid instrument behaves as a pure quantity instrument when the cap is binding, and behaves as a pure price instrument when the permit price exceeds the trigger price. Therefore, the expected net benefits of a hybrid will by definition be the weighted average of the expected net benefits for the quantity and price instruments, and the weight is the probability that the price is triggered. For a stock pollutant, a hybrid with a trigger price equal to the optimal price instrument and an emissions cap of zero will be optimal, since it simulates the price instrument (e.g., carbon tax). An indexed quantity instrument improves upon a pure quantity instrument, but the added benefit depends critically on the correlation between abatement costs and the index. For any indexed quantity instrument with a correlation of less than unity, a hybrid can be constructed that is preferred by setting its emissions cap low enough to raise the probability of triggering the price component, and therefore coming close to a pure price instrument. We will show below that the critical comparison is between the correlation of the indexed regulation and the trigger probability of the hybrid.

2. Model of pollution externality

In order to derive the expected net benefits of a hybrid instrument under uncertainty, we begin by reviewing the basic Weitzman [3] model and results. Benefits and costs are modeled as second order Taylor Series expansions about the expected optimal abatement quantity target q^*. Costs and benefits, respectively, are defined as

$$C(q) = c_0 + (c_1 - \theta_c)(q - q^*) + \frac{c_2}{2}(q - q^*)^2, \tag{1}$$

$$B(q) = b_0 + b_1(q - q^*) - \frac{b_2}{2}(q - q^*)^2. \tag{2}$$

We assume that $c_2 > 0$ and $b_2 \geq 0$; i.e., costs are strictly convex and benefits are weakly concave. θ_c is a random shock to costs with expectation 0 and variance σ_c^2. As in Newell and Pizer, we define θ_c such that a positive shock reduces the marginal cost of producing q. Weitzman [3] showed that the net gain from a price instrument relative to a quantity instrument is

$$\Delta_{p-q} = \frac{(c_2 - b_2)\sigma^2}{2c_2^2}, \tag{3}$$

when the slope of the marginal costs exceeds the slope of the marginal benefits, a price instrument is preferred. For a pure stock pollutant (b_2=0), the price instrument is always preferred.

3. Second-best instruments for cost-containment

We now extend this model to represent a hybrid instrument or safety valve. We will first derive the expression for the expected net benefits of the safety valve. We then derive the expressions for the net gain from an intensity target relative to a safety valve, and show the general conditions under which each instrument is preferred.

3.1. Expected net benefits of hybrid instrument

A hybrid regulatory instrument consists of both a quantity and a price instrument. An emissions cap is set, just as in a pure quantity instrument, and emissions permits are allocated among emitters, which they are allowed to trade. In addition, the regulatory agency will sell additional permits at some trigger price p, for as many permits as are necessary. Thus p establishes a ceiling on the permit price; it can never rise above this level. If the permit price is below p, a rational agent will either buy a permit from the market or abate, and the regulation behaves like a quantity regime. If the emissions limit is stringent enough for the permit price to rise above p, agents will buy additional permits from the government and, for the purposes of calculating net benefits, the regulation behaves like a price instrument.

The resulting net benefits from the hybrid instrument, as for quantity and price instruments, depend critically on the choice of the emissions limit and the trigger price. As in Weitzman [3] and in Newell and Pizer [6], we wish to assume optimal choices of these design variables. However, there is immediately a difficulty: we know from the Weitzman result, as summarized above, that the optimal hybrid instrument consists of an emissions limit of zero (i.e., no allowances) and an optimal trigger price equal to the optimal pure tax. A hybrid instrument with a non-zero emissions limit is inherently a second-best instrument as compared with a pure price instrument, but may be necessary when a price instrument is not politically feasible. We therefore proceed for the remainder of this paper under the assumptions that: (1) a pure emissions tax is not feasible, and (2) the emissions limit for a hybrid instrument will be given as an outcome of some political process. The question we address here is under what conditions is a hybrid instrument with some non-zero cap preferable to an intensity target with an equivalent cap.

We show in the Appendix that the optimal trigger price for a hybrid instrument does not depend on the emissions cap, and under simplifying assumptions can be solved as

$$p^* = \left(1+\frac{b_2}{c_2}\right)^{-1} b_1 + \left[1-\left(1+\frac{b_2}{c_2}\right)^{-1}\right](c_1+\delta). \tag{4}$$

In general, the optimal trigger price will be a weighted average between the marginal benefits and the marginal cost in the high cost case, where the relative weight of the terms depends on the relative slopes of marginal costs and benefits. The optimal trigger price will be higher than the marginal benefits (the optimal price for a pure price instrument) for a downward sloping marginal benefit curve. However, Pizer [14] argues for a stock pollutant, such as greenhouse gases, that b_2 can be treated as approximately zero (constant marginal benefits). In this case, the optimal trigger price reduces to simply $p^*=b_1$. The optimal trigger price for a hybrid instrument for a stock pollutant is the same as the optimal tax, equal to the marginal benefits.

This result for the optimal trigger price is essentially the ceiling price for the hybrid policy of Roberts and Spence [15]. Roberts and Spence showed that for a general pollution externality, the optimal instrument was a hybrid with an emissions cap, a ceiling price, and a floor price (or subsidy), which is preferred over a pure cap or a pure tax. The intuition is that the step function created by policy approximates the marginal benefit function. For the special case of constant marginal benefits, this optimal hybrid converges to a pure price instrument equal to the marginal benefits. Henceforth, we restrict our consideration to pure stock pollutants for which we will assume that the marginal benefits in any single period are essentially constant (b_2=0) so that the optimal trigger price equals the marginal benefits at the expected level of abatement (q^*).

For any distribution of θ around zero and any choice of cap q, the trigger price will be activated with probability π, and the emissions limit will be binding with probability $1-\pi$, where the probability π is a function of the distribution of θ and the choice of the cap q. The expected net benefits of a hybrid instrument under these conditions is

$$\begin{aligned} E\{NB_{sv}\} &= (1-\pi)E_\theta\left[b_0-c_0+(b_1-c_1-\theta)(q^*-q^*)-\frac{(b_2+c_2)}{2}(q^*-q^*)^2\right] \\ &\quad +\pi E_\theta\left[b_0-c_0+(b_1-c_1-\delta)\left(q^*+\frac{\theta}{c_2}-q^*\right)-\frac{(b_2+c_2)}{2}\left(q^*+\frac{\theta}{c_2}-q^*\right)^2\right], \\ &= E_\theta\left\{b_0-c_0+\pi\frac{(b_1\theta-c_1\theta)}{c_2}+\pi\frac{(c_2-b_2)\theta^2}{2c_2^2}\right\} = b_0-c_0+\pi\frac{(c_2-b_2)\sigma^2}{2c_2^2}. \end{aligned} \tag{5}$$

Thus the additional net benefit of a hybrid relative to a quantity instrument is

$$\Delta_{sv-q} = \frac{\pi(c_2-b_2)\sigma^2}{2c_2^2} = \pi\Delta_{p-q}. \tag{6}$$

For the special case where the distribution for θ is symmetric and the emissions cap is set to the optimal quantity instrument q^*, then $\pi=1-\pi=0.5$ and the advantage of the safety valve relative to a quantity instrument is exactly half the advantage of the price instrument over the quantity instrument, $\Delta_{sv-q}=\Delta_{p-q}/2$. A tighter emissions cap $q<q^*$ in the hybrid will have a higher probability $\pi>0.5$ of triggering the price instrument, therefore a greater advantage over a pure quantity instrument.

This result, that a hybrid that triggers the price half the time has only half the additional benefits of the pure price instrument, is consistent with conceptual studies (e.g., [8,16,17]). Pizer [5] used a quantitative model to show that the optimal hybrid for a stock pollutant had a trigger price equal to the optimal pure price instrument, and an emissions cap that was significantly more stringent than the pure quantity instrument (5 GtC vs. 13 GtC), which clearly will trigger the price instrument more than 50% of the time. Finally, as discussed above, Roberts and Spence [15] show in their more general model that the optimal hybrid for a pure stock externality is a pure price instrument (no cap). Adding a quantity constraint that is binding some fraction of the time will reduce the expected net benefits.

3.2. Safety valve vs. general indexed quantity

Intensity targets, where the emissions limit is determined from the GDP which is uncertain and a desired emissions intensity ratio, fall under the general category of indexed quantity instruments. The most general form of indexed quantities, which Newell and Pizer [6] refer to as a General Indexed Quantity (GIQ) chooses emissions q as a linear function of another random variable x as

$$q(x) = a + rx, \tag{7}$$

where a and r are policy design variables and $E\{x\} = \bar{x}$, $\text{var}(x) = \sigma_x^2$, and $\text{cov}(x,\theta) = \sigma_{cx}$. The optimal choice of an indexed quantity is

$$q^*_{GIQ}(x) = q^* + r^{**}(x - \bar{x}), \tag{8}$$

where $r^{**} = (\sigma_{cx}/\sigma_x^2)/(b_2 + c_2)$. The resulting expected net benefits are

$$E\{NB_{GIQ}\} = b_0 - c_0 + \frac{\sigma_c^2}{2(c_2+b_2)}\rho_{cx}^2. \tag{9}$$

We are interested here in when a hybrid instrument is preferred over an intensity target or vice versa. When the distribution of θ is symmetric, the expected net benefits of the hybrid is as given in Eq. (9). Comparing with Eq. (6), the indexed quantity will be preferred when

$$\frac{\sigma_c^2}{2(c_2+b_2)}\rho_{cx}^2 > \frac{(c_2-b_2)\sigma_c^2}{2c_2^2}\pi.$$

Rearranging to solve for ρ, the intensity target is preferred when

$$\rho_{cx}^2 > \frac{(c_2-b_2)(c_2+b_2)}{c_2^2}\pi. \tag{10}$$

For the case of a stock pollutant, where $b_2 \cong 0$, this simplifies to

$$\rho_{cx} > \sqrt{\pi}. \tag{11}$$

Eq. (11) is a simple and powerful result: for a stock pollutant, indexed regulation is preferred when the square of the correlation (the coefficient of determination) is greater than the probability of triggering the price instrument in the hybrid. Intuitively, an indexed quantity instrument with correlation of unity would be equivalent to the pure price instrument, which is the optimal instrument; a hybrid that always triggers its price component is also equivalent to the pure price instrument. Whichever instrument is closer to the optimal carbon tax will therefore be preferred.

For example, if the distribution is symmetric and the probability of activating the trigger price is 0.5, then the intensity target would be preferred when the correlation ρ_{cx} exceeds $1/\sqrt{2} \cong 0.71$. As one should expect, the indexed quantity instrument is preferred when the correlation between emissions and the index quantity (e.g., GDP) is high enough. If the correlation were perfect, $\rho=1$, then the indexed quantity would be preferred. If there was no correlation, $\rho=0$, the hybrid would be preferred.

For any indexed quantity instrument with correlation ρ, a pareto superior hybrid can be constructed by simply tightening the emissions cap. If the cost uncertainty is assumed to be normally distributed, there is no closed-form analytical expression for the cumulative probability of triggering the price component of the hybrid as a function of the emissions cap q. However, we can use Eq. (11) to calculate the emissions cap in the hybrid required for the hybrid to be preferred to the index quantity instrument. Table 1 shows these values for several illustrative values of the correlation in the index instrument. The probability of triggering the price component must be greater than or equal to the square of the correlation, and the z-value from a standard normal is given for each cumulative probability. The z-value can be transformed for a particular situation by multiplying by the standard deviation of the cost uncertainty s_c and dividing by

Table 1
Required minimum adjustment in hybrid emissions cap for hybrid to be preferred to intensity target.

Correlation ρ	Probability π	$z=\Phi(\pi)^{-1}$	ΔEmis. Cap$^*=z^*\sigma_c/c_2$	New cap[a]	%ΔCap[a]
0.7	0.49	−0.03	−15.0	5042.0	+0.3
0.75	0.56	0.16	94.4	4932.6	−2
0.8	0.64	0.36	215.1	4811.9	−4
0.85	0.72	0.59	354.2	4672.8	−8
0.87	0.76	0.70	417.8	4609.2	−9
0.9	0.81	0.88	526.7	4500.3	−12
0.95	0.90	1.30	777.6	4249.4	−18
0.99	0.98	2.06	1233.5	3793.5	−33

[a] Values in columns 4–6 for a sample case where the standard deviation in cost σ=\$10/ton CO_2, slope of marginal cost curve c_2=1/60=0.1667\$/mmt CO_2, and the original cap q=5027 mmt CO_2.

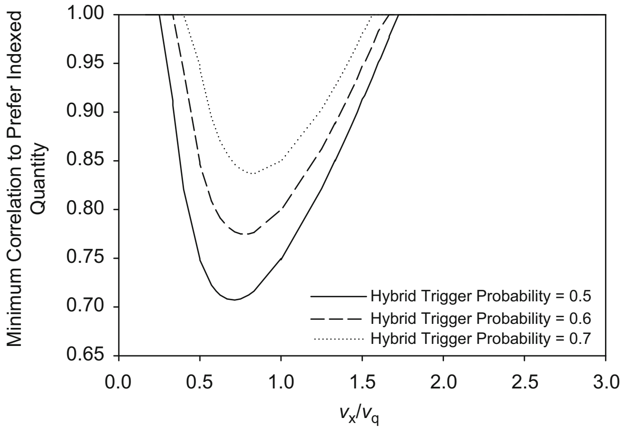

Fig. 1. Critical correlation between index and cost uncertainty for an indexed quantity instrument to be preferred over a hybrid, as a function of the ratio of the coefficients of variation for indexed quantity *x* and emissions *q*. The critical value for correlation depends on the probability that the price component of the hybrid is triggered, which is a function of the emissions cap chosen. Results are shown for three sample values of the probability of price trigger in the hybrid: 0.5, 0.6, and 0.7.

the slope of the marginal cost curve, c_2. Table 1 also provides values of the adjusted hybrid cap for an example where σ_c=\$10/ton CO_2, c_2=1/60=0.1667\$/mmt CO_2 and the original cap q^*=5027 mmt CO_2.

3.3. Safety valve vs. indexed quantity

The most common form of intensity target under consideration in climate policy discussions would not take the general form of the indexed quantity as described above. Newell and Pizer point out that a GDP-based intensity target would set the variable *a* in Eq. (7) to zero. They refer to this instrument as an Indexed Quantity (IQ), in contrast to the GIQ above, and its optimal form is

$$q^*_{IQ}(x) = r^* x, \quad (12)$$

where $r^* = (1+\nu_x^2)^{-1}((q^*/\bar{x}) + \nu_x^2 r^{**})$ and $\nu_x = \sigma_x/\bar{x}$. If $\rho_{cx} \neq 0$, the expected net benefits for the indexed quantity is

$$E\{NB_{IQ}\} = b_0 - c_0 + \frac{\sigma_c^2}{2(c_2+b_2)}\rho_{cx}^2\left(1 - \frac{1}{1+\nu_x^2}\left(1 - \frac{\nu_x}{\rho_{cx}\nu_{q^*}}\right)^2\right), \quad (13)$$

where $\nu_{q^*} = (\sigma_c/(b_2+c_2))/q^*$.

Comparing Eqs. (6) and (13), the critical correlation where the relative net benefits of IQ are positive is a quadratic function of the ratio of the coefficient of variation (the standard deviation relative to the mean) of the indexed quantity (GDP) to the coefficient of variation of the emissions, v_x/v_q. Fig. 1 shows this relationship over a wide range of possible values of v_x and v_q for sample values for the hybrid price trigger probability π=0.5, 0.6, and 0.7 (Fig. 1). If the ratio v_x/v_q is less than 0.25 or greater than 1.8, the hybrid instrument is always preferred. Thus the intensity target is most useful in cases where the magnitude of the uncertainties in cost and the index are roughly comparable, as also suggested by Newell and Pizer. For ratios between 0.25 and 1.8, the minimum correlation for which one would be indifferent between the two instruments follows the curves in Fig. 1. Note that for a trigger probability π=0.5 and a ratio of v_x/v_q=0.71 (corresponding to $v_x/(v_q\rho_{cx})$=1), the indexed quantity has the same indifference correlation as the general indexed quantity, $1/\sqrt{2}$. For higher trigger probabilities, the range of the ratio v_x/v_q and the correlation ρ for which the index quantity is preferred is an increasingly narrow space, as expected.[1]

4. Numerical example

We illustrate the above analytical expressions by performing an uncertainty analysis on a computable general equilibrium model of the US economy, and show the conditions under which an intensity target will be preferred to a safety valve or vice versa. We first briefly describe the model and the uncertainty analysis, then give the results from the model and compare to the analytical model from the previous section.

[1] Newell and Pizer [18] give observed values of ρ, v_x, and v_q for 19 different countries. For the given values, an indexed quantity instrument would only be preferred to a hybrid with a trigger probability of 0.5 for Brazil and China, and for no countries would it be preferred to a hybrid with a trigger probability of 0.55 or greater.

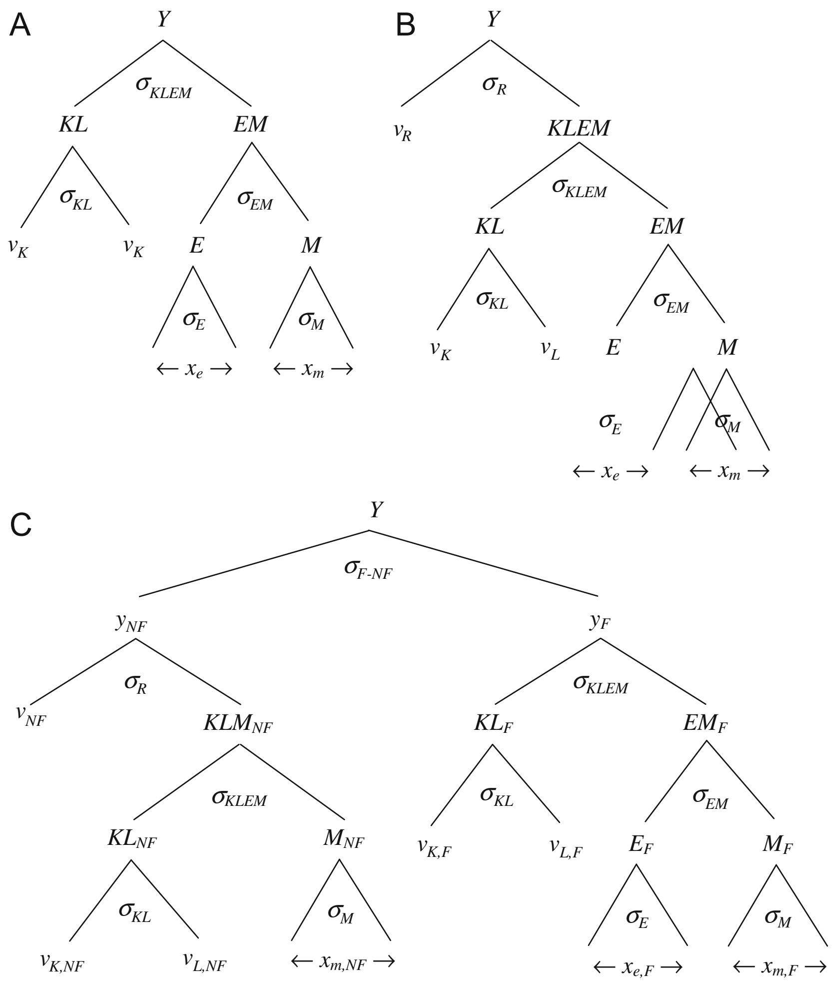

Fig. 2. The structure of production in the CGE model. (A) Non-Primary Sectors; (B) Primary (Resource) Sectors; (C) Electric Power Sector.

4.1. *Model description*

We test the predictions of the preferred instrument using a static CGE model of the US. The model treats households as an aggregate representative agent with constant elasticity of substitution (CES) preferences. Industries are consolidated into the 11 sectoral groupings shown in Table 3, and are treated as representative firms with nested CES production technology. For this purpose we adapt Bovenberg and Goulder's [19] KLEM production technology and parameterization, as shown in Fig. 2.[2]

The model's algebraic structure is numerically calibrated using US data on inter-industry economic flows, primary factor demands, commodity uses and emissions in the year 2004. We simulate prices, economic quantities, and emissions of CO_2 in the year 2015 by scaling both the economy's aggregate factor endowment and the coefficients on energy within industries' cost functions and the representative agent's expenditure function. The probability distributions of these scaling factors, when propagated through the model, give rise to probability distributions for the future value of baseline national income, energy use and emissions. This model only represents CO_2 emissions, and does not include the emissions or abatement costs of other greenhouse gases.

The parameters which govern the malleability of production are the elasticities of substitution between composites of primary factors (*KL*) and intermediate inputs (*EM*), which we denote σ_{KLEM}; between inputs of capital (*K*) and labor (*L*), denoted by σ_{KL}; between energy (*E*) and materials (*M*), indicated by σ_{EM}; and among different intermediate energy and material commodities (*e* and *m*), denoted by σ_E and σ_M, respectively. In natural resource-dependent sectors (e.g., production of primary fuels such as coal) the resource is modeled as a fixed factor which enters at the top of the

[2] Additional details are contained in an appendix that is available at JEEM's online archive of supplementary material, which can be accessed at http://aere.org/journals/.

production hierarchy, governed by the elasticity σ_R. The electric power sector encompasses two nested production structures, one for primary electricity generated from fixed factors (e.g., nuclear, hydro and wind), which exhibits features of resource-dependent sectors, and another representing fossil fuel generation which exhibits features of non-resource sectors. Probability distributions for these seven parameters, when propagated through the model, generate probability distributions for the changes in income and emissions from their baseline levels in response to climate policy.

4.2. Parametric uncertainty

For this analysis of near-term carbon abatement policies, we consider uncertainty in three categories of parameters: the GDP growth rate of the economy between 2005 and 2015, the rate of autonomous energy efficiency improvement (AEEI), and the elasticities of substitution in the production functions. We briefly summarize here the probability distributions for the uncertainty parameters (see [20] for a more detailed description).

Annual GDP growth rates are modeled as a random walk with drift [21,22]. The volatility is estimated from GDP time series data for the US economy from 1970 to 2000 [23]. For projecting from 2005 to 2015, instead of the historical mean growth rate, we use the reference EIA forecast [24] growth rate of 3% per annum. Our estimated volatility results in a distribution of future growth rates with $\pm$ one standard deviation almost identical to the EIA high and low growth cases.

The AEEI parameter has a reference (mean) value of 1.0% p.a., consistent with many other energy economic models [25]. The uncertainty in AEEI is assumed to be normal with a standard deviation of 0.4% based on several analyses [26,27].

The uncertainties in the elasticities of substitution are based on literature survey of econometric estimates with published standard errors. The details of this survey and the synthesis of the standard errors into a probability distribution for each elasticity are documented fully in Webster et al. [20]. The empirical probability distributions for each of these parameters are summarized in Table 1, along with representative statistics.

4.3. Results of CGE model

We perform Monte Carlo simulation on the CGE model, drawing 1000 random samples of parameter values. In addition to the reference (no policy) case, we impose four types of policy constraints: an emissions cap, a carbon tax, a safety valve, and an intensity target. The stringency of the emissions cap is defined as the expected CO_2 abatement under the McCain–Lieberman Senate Bill [1] of 2100 Mt CO_2, leaving US emissions in 2015 at 5000 Mt CO_2, and at a marginal cost of \$23/ton CO_2. We define all other policy instruments such that they will be equivalent in the reference or mean case; the carbon tax is \$23/ton CO_2, the trigger price of the safety valve is \$23/ton CO_2, and the intensity target requires an emissions/GDP ratio to be the same as that which results under the quantity instrument in the mean case. Finally, a critical assumption in the results shown here is that the marginal benefit of CO_2 abatement in 2015 is assumed to be \$23/ton CO_2; i.e., we assume that the imposed policies are all optimal in the no-uncertainty case.

The mean and standard deviations for key results are given in Table 2. The expected abatement of CO_2 is the same for all instruments except the safety valve, which abates less than the others. The safety valve also has greater uncertainty in the abatement than either the tax or intensity targets, but less than the emissions cap. The uncertainty in marginal costs of abatement are greatest for the cap and no uncertainty for the tax (by definition), with the safety valve having the next smallest uncertainty. Expected net benefits (calculated assuming a marginal benefit of abatement of \$23/ton) are, consistent with theory, greatest for the tax and least for the cap. The safety valve and the intensity target have similar expected net benefits, but the intensity target is preferred. The correlation between GDP and emissions in the no policy case is calculated as 0.87, so this is consistent with the expressions in Section 3.

To further test the consistency between the CGE and analytical models, we construct an experiment to artificially vary the correlation between GDP and emissions in the Monte Carlo simulation. We cannot directly impose a correlation, since the emissions are an endogenous function of GDP growth and other factors. Instead, we artificially increase or decrease the

Table 2
Uncertain parameter distributions for Monte Carlo simulations.

	AEEI (%/yr)	GDP growth (%/yr)	Elasticities of substitution					
			$\sigma_{F\text{-}NF}$	σ_{KLEM}	σ_{KL}	σ_{EM}	σ_E	σ_M
Mean	1.0	2.8	1.0	1.1	1.1	1.0	1.0	1.0
St. dev.	0.4	0.8	0.5	0.5	0.6	0.4	0.5	0.5
0.025	0.2	1.2	0.1	0.2	0.1	0.3	0.2	0.1
0.05	0.3	1.4	0.2	0.3	0.2	0.4	0.3	0.2
0.25	0.7	2.3	0.7	0.7	0.6	0.7	0.7	0.7
0.5	1.0	2.9	1.0	1.1	1.1	1.0	1.0	1.0
0.75	1.3	3.4	1.3	1.4	1.6	1.3	1.3	1.4
0.95	1.7	4.1	1.8	1.8	2.3	1.7	1.8	1.9
0.975	1.8	4.4	1.9	2.0	2.5	1.8	2.0	2.0

variance of the GDP growth rate uncertainty, while holding constant the variance of AEEI and the elasticities of substitution. This procedure causes the correlation between GDP and emissions to vary across different sets of random samples.

Six different sets of random samples are drawn, with correlation between GDP and emissions ranging from 0.65 to 0.93. The value of correlation for which one would be indifferent between the intensity and safety valve instruments is 0.86 (Fig. 3). In contrast, the coefficients of variation for GDP and emissions from the CGE model are 0.79 and 0.84, respectively, giving a ratio v_x/v_q equal to 0.94. The relationship plotted in Fig. 1 predicts an indifference correlation value of 0.74 for these parameter values.

The divergence in the indifference point correlation between the CGE model and the analytical model results from the non-linearity of the marginal abatement cost from the model. Our analytical model, like Weitzman's model, assumes linear marginal costs, whereas the marginal costs predicted by the CGE model are approximately cubic. A non-linear marginal cost curve favors a policy in which the expected abatement is lower than the optimal abatement under certainty (the reference cap), because beyond the point of optimal abatement marginal costs are steeply increasing. As an illustration, we use the average marginal abatement cost curve from 1000 runs of the CGE model (Fig. 4), and calculate the loss in net benefits from 1000 mmt more or less than optimal abatement; the net benefit loss in area B, $14,797B, is more than twice that of area A, $8873B. A safety valve will always result in abatement less than or equal to the reference cap, while an intensity target may require abatement either above or below the reference cap. Non-linear marginal costs thus induce a bias in favor of the safety valve, as the instrument operates solely in the region where marginal costs are favorable. We should thus expect that the CGE model with cubic marginal costs will predict a higher indifference point correlation than the analytical model, which is what we see here.

To test this hypothesis, one would ideally perform an identical experiment except with linear marginal abatement costs. However, there is no simple way to modify a CGE model to induce global linearity. As an approximation, we impose a less stringent emissions target (6200 mmt) in the CGE model, such that the relevant portion of the marginal cost curve is nearly linear. We repeat the above Monte Carlo experiments, for several different assumed variances for the GDP uncertainty, and calculate the expected net benefits under the hybrid and indexed instruments (Fig. 3). Under the less stringent target, the critical value of correlation for which the intensity target becomes preferred over the safety valve is 0.74, as predicted by the analytical model.

Table 3
Results of Monte Carlo simulations.

	Emissions (Mton CO_2)		Abatement (Mton CO_2)		Carbon price (\$/ton CO_2)		Net benefits (\$M)	
	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.
No policy	7079	593	–	–	–	–	–	–
Cap	5027	0	2052	593	23.0	10.8	23,231	5118
Tax	4982	473	2099	322	22.7	0.0	25,341	3738
Safety valve	5191	257	1887	453	18.7	5.1	24,273	4451
Intensity	4971	393	2108	316	23.8	7.7	24,363	4423

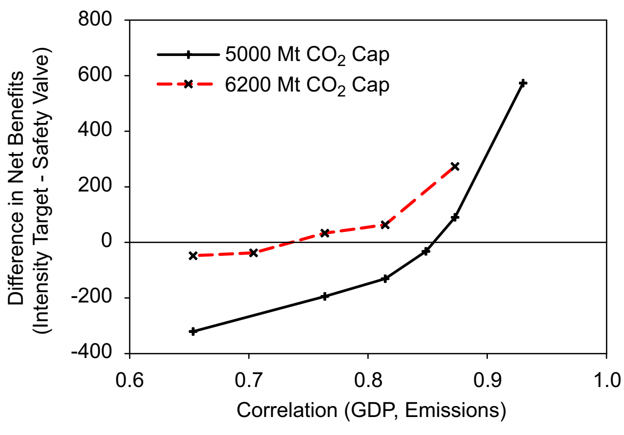

Fig. 3. Relative advantage of intensity target over safety valve as a function of the correlation between GDP and baseline emissions. For an emissions target of 5000 mmt, a higher correlation (at least 0.86) is necessary for the intensity target to be the preferred instrument. For a less stringent target (6200 mmt), for which the relevant portion of the MAC curve is nearly linear, the indifference point between the intensity target and safety valve occurs at 0.74, as was predicted by the analytical model.

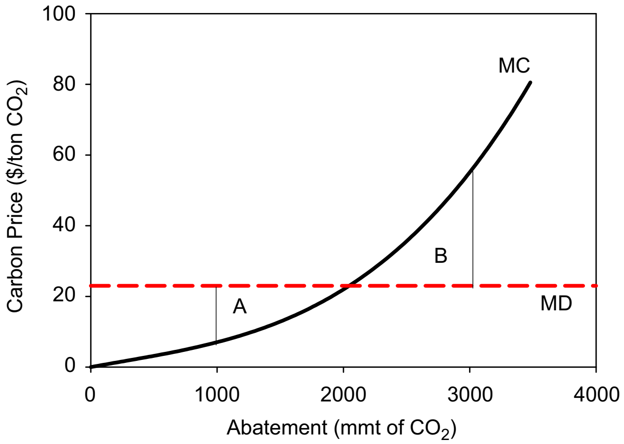

Fig. 4. Loss in expected net benefits in CGE model from abatement 1000 mmt less than optimal and 1000 mmt more than optimal. Area A represents the net benefits lost from abating too little ($8873B), which is substantially smaller than area B, the net benefits lost from abating too much ($14,797B).

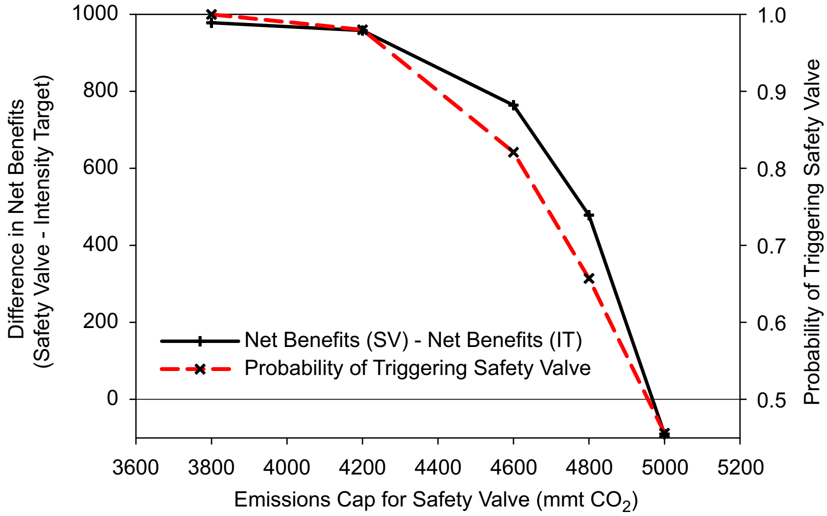

Fig. 5. The net benefits of the hybrid over the intensity target as a function of the emissions cap in the hybrid, shown for the reference case with an original emissions cap of 5000 mmt and a correlation between index and costs of 0.87. The dashed line shows the probability of triggering the price component of the hybrid as a function of the emissions cap.

The preferred policy instrument is thus dependent on the slope of the marginal cost curve over the range of potential abatement. Because the actual economy is unlikely to have strictly linear marginal abatement costs, the range of conditions in which the intensity target is preferable to the safety valve, especially given a reasonably stringent emissions target, is probably quite narrow.

As shown in Section 3, the relative advantage of a hybrid over an indexed quantity depends on the trigger probability of the hybrid, which in turn depends on the emissions cap set. For the reference case where the correlation is 0.87 and the optimal quantity instrument is 5000 mmt, Fig. 5 shows how the relative expected net benefits of the hybrid over the indexed quantity increases as the hybrid cap is tightened. Note that initially, small increases in cap stringency result in large improvements in the relative net benefits of the hybrid, after which further increases in stringency have diminishing improvements. As the trigger probability approaches 1, the relative net benefits approach those of the pure price instrument.

5. Discussion

Given the uncertainty in economic growth and the cost of abating CO_2 emissions, an emissions cap chosen today for some future year has the potential for higher than expected abatement costs and a consequent welfare loss. The preferable economic instrument for a stock pollutant, a carbon tax, seems politically infeasible at least in the US and perhaps in other countries as well. This leads to interest in either a safety valve or an intensity target as a regulatory instrument that has less uncertainty in the cost of abatement and welfare losses.

Our analysis has shown that, if both instruments are designed to be equivalent in the no uncertainty case, then under uncertainty a high correlation (at least 0.7 and usually higher) between the cost uncertainty and the index uncertainty is required to justify the choice of an intensity target as a regulatory instrument over a safety valve that is triggered at least 50% of the time. The design details of the actual policy are critical to the choice between instruments. For example, a hybrid with a trigger price much lower than the marginal benefits will be much less efficient, and an intensity target may be superior. On the other hand, multiple greenhouse gas targets are likely to have a far lower correlation between abatement costs and any single index such as GDP.

The analysis presented here focuses exclusively on a single period of relatively few years. For longer time frames divided into multiple periods, an additional question is how banking and borrowing of emissions permits would perform relative to either a safety valve or an intensity target. Finally, there is a question about how a single period analysis that allows emissions to be higher or lower in response to uncertainty can be made consistent with a long-term target, such as concentration stabilization, where less abatement in one period must be compensated by abatement in another period.

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