

December 2005 ■ RFF DP 05-[##]

Indexed Regulation

Richard G. Newell
William A. Pizer

1616 P St. NW
Washington, DC 20036
202-328-5000 www.rff.org



RESOURCES
FOR THE FUTURE

Indexed Regulation

Richard G. Newell and William A. Pizer

Abstract

Seminal work by Weitzman (1974) revealed that prices are preferred to quantities when marginal benefits are relatively flat compared to marginal costs. We extend this comparison to indexed policies, where quantities are proportional to an index, such as output. We find that policy preferences hinge on additional parameters describing the first and second moments of the index and the ex post optimal quantity level. When the ratio of these variables' coefficients of variation divided by their correlation is less than 2, indexed quantities are preferred to fixed quantities. A slightly more complex condition determines when indexed quantities are preferred to prices. Applied to the case of climate change, we find that quantities indexed to GDP are preferred to fixed quantities for about half of the 19 largest emitters, including the United States and China, while (consistent with previous work) prices dominate for all countries.

Key Words: price, quantity, regulation, uncertainty, policy, environment, climate change

JEL Classification Numbers: Q28, D81, C68

Contents

| | |
|--|------------|
| Abstract | ii |
| Contents | iii |
| 1. Introduction | 1 |
| 2. Model and Analytic Results | 6 |
| 2.1. Review of Prices versus Quantities..... | 7 |
| 2.2. General Indexed Quantities..... | 10 |
| 2.3. (Ordinary) Indexed Quantities | 13 |
| 2.4. The Advantage of Indexed Quantities Relative to Prices and Quantities | 16 |
| 2.5. Summary of the Relative Advantages of Alternate Policies..... | 19 |
| 3. An Application to Environmental Policy | 20 |
| 3.1. Decomposition of Cost Shocks | 21 |
| 3.2. Climate Change Policy Parameters..... | 22 |
| 3.3. Country-level Emissions and GDP Data..... | 24 |
| 3.4. The Relative Advantage of Alternate Climate Policies | 26 |
| 4. Conclusions | 28 |
| Figures and Tables | 30 |
| References | 38 |

Indexed Regulation

Richard G. Newell and William A. Pizer*

1. Introduction

The literature on policy instrument choice under uncertainty has historically focused on the relative performance of prices, quantities, and hybrid price-quantity instruments (Weitzman 1974; Roberts and Spence 1976; Weitzman 1978; Yohe 1978; Stavins 1996; Pizer 2002; Newell and Pizer 2003). In practice, however, the decision for policymakers often comes down to choosing among different types of quantity-based instruments, not choosing between prices and quantities. Nowhere is this better illustrated than the current debate on the form and implementation of measures to address global climate change. While the Kyoto Protocol and the European Union's Emission Trading Scheme for carbon dioxide focus on a quantity-based system with fixed emission targets, the United States and Australia have embraced targets based on emission intensity—a quantity target indexed to economic activity. Canada has committed to a quantity target under the Kyoto Protocol, but it is pursuing an intensity-based target in its domestic program. Few countries have chosen the relevant price instrument, a carbon tax, and this option is politically taboo in the United States.¹

This paper considers the welfare implications of this indexed versus fixed quantity distinction and reveals a simple condition for preferring one to the other. When the coefficient

* Newell and Pizer are Senior Fellow and Fellow, respectively, at Resources for the Future, Washington, DC. We thank Drew Baglino for research assistance and Carolyn Fischer, Ulf Moslener, John Parsons, Wally Oates, Brian McLean, David Evans, and participants in seminars at RFF, FEEM, HEC Montréal, and the Southern Economic Association Annual Meetings, for useful comments on previous versions of the paper. We acknowledge funding from MISTRA, the Swedish Foundation for Strategic Environmental Research.

¹ New Zealand initially adopted then rejected a carbon tax; Japan recently considered but did not enact proposals for a carbon tax. Canada's intensity-based approach also includes a price-based safety valve.

of variation in the index divided by the coefficient of variation in the ex post optimal quantity level is less than twice their correlation, indexed quantities are preferred. Applying these results to the question of indexed versus fixed emission limits to address global climate change, we find that indexed limits are preferred for about half the countries we examine, including the United States.

Of course interest in indexed and fixed quantity regulation is not limited to climate change. Environmental policy in the United States is replete with examples of both kinds of quantity policies. The most familiar example to many is the U.S. sulfur dioxide tradable permit or “cap-and-trade” system for electricity generators (Stavins 1998; Carlson et al. 2000). Since 1995, this system has set a fixed limit on the tons of sulfur dioxide emitted from power plants, while allowing sources to trade emission allowances in order to minimize compliance costs. The NO_x Budget Program, the Clean Air Interstate Rule, and Clean Air Mercury Rule (all promulgated by the Environmental Protection Agency under the Clean Air Act), along with a host of regional air and water trading programs round out the U.S. experience with fixed targets.

Despite these examples, performance standards are a more common form of environmental regulation, typically set in terms an allowable emission rate per unit of product output (i.e., emission intensity) (Russell et al. 1986; Helfand 1991). The phasedown of lead in gasoline—the first large-scale experiment with market-based environmental policy—employed a tradable performance standard (Nichols 1997; Kerr and Newell 2003). Eighteen states now have (and the U.S. Senate has proposed) renewable portfolio standards that require a certain share of electricity generation from renewable sources (Union of Concerned Scientists 2005). Corporate Average Fuel Economy (CAFE) standards are a less flexible performance standard that can be traded and banked within but not across firms (e.g., across vehicle lines within a firm). Even less flexible are traditional command-and-control style regulations, such as New Source Performance Standards.

Like an intensity target for greenhouse gases, these forms of regulation allow the effective emission cap to adjust in response to changes in output. This feature has political appeal because it provides a way to set environmental standards that are less likely to be, or perceived to be, constraints on economic growth, either within a regulated sector or across the economy. Intuition suggests that the responsiveness of intensity-based quantity regulation to output changes may also have economic appeal. Such adjustments could lower the expected costs of achieving a particular environmental target by loosening the cap when costs are unexpectedly high and tightening it when costs are low.² This is analogous to the cost advantage of prices over quantities identified in the literature.

On the other hand, including an index in the policy formula introduces another uncertain variable, and potentially unrelated noise, which could have negative consequences on efficiency. The purpose of this paper is to clarify these tradeoffs by identifying the key features of the regulatory problem, modeling the relative performance of fixed versus indexed quantity targets, and applying the resulting framework to country-level data relevant for climate policy. We note now and at several later points that all of our theoretical results apply, almost without modification, to the case of indexed price policies, though the lack of both general support for price regulation and the absence of any real-world examples of indexed prices makes them less interesting.³

Several recent papers have looked both theoretically and empirically at the relative advantages of intensity targets in the case of climate change policy. Quirion (2005) presents a theoretical model with uncertain baseline emissions along with uncertainty in costs, observing that strong positive correlation favors indexed quantities, similar to our results. His analytic

² Linking an emission limit to output raises questions of both subsidizing output and creating pro-cyclical costs, points we consider at the end of this paper.

³ The obvious exception being the large number of policies and contracts with nominal values indexed to inflation, as well as natural gas contracts that are sometimes indexed to crude oil prices.

model differs from ours in that he focuses on a perfect index for baseline emissions, rather than a general index for cost shocks, and his overall conclusions are more qualitative. He argues that plausible assumptions imply indexed quantities typically lie between prices and quantities in terms of expected net benefits, a somewhat different result than our own.

Focusing solely on costs (and ignoring benefits), Ellerman and Sue Wing (2003) employ a simulation model to argue that partial indexing—what we call a general indexed quantity—is more sensible. Such an approach sets the mean emission level and the rate of adjustment to the index separately, rather than allowing a single parameter (the emission rate) to determine both.⁴ Similar to Ellerman and Sue Wing, Jotzo and Pezzey (2005) derive an optimal indexing rule based on minimizing expected costs and use a simulation model to evaluate both a general indexed quantity policy and a ordinary, proportional indexed quantity policy. They conclude that for climate policy, indexes of either type are better than fixed quantity policies at a global level, that the more general index is considerably better than ordinary indexing, and that the rate of indexing varies greatly among countries.

Finally, Sue Wing et al. (2005) conclude that sufficiently small GDP variance and high correlation favor indexed quantities for climate policy—as we do—but based on minimizing expected costs rather maximizing expected benefits minus costs. They also present empirical evidence supporting indexed quantities over fixed quantities with strong support for developing countries and more equivocal results for industrialized countries.

Our work ties together and clarifies this literature by deriving simple analytic expressions for the advantage of indexed quantities relative to both price and quantity controls. Three conditions lead to a preference for indexed quantities: positive correlation of the index and

⁴ Compare $q = a + rx$ with and without the parameter a , where q is emissions, x is the index, and r is the rate of adjustment to the index. We address the distinction between general and ordinary (proportional) indexing further below.

marginal abatement cost uncertainty, relatively small index variance, and sufficiently steep marginal benefits. The intuition is straightforward. With low correlation, indexing introduces unwanted noise in the target without reducing cost uncertainty. Further, a large index variance, relative to the marginal cost variance, will over adjust quantities even if there is perfect correlation. Finally, if marginal benefits are flat, prices achieve the first-best outcome, leaving quantities—indexed or not—behind.

Applying the analytic results to the case of climate change, we show the ranking of these instruments for major emitting countries using data from the Energy Information Administration and previous work on marginal costs and benefits of greenhouse gas mitigation. Prices are always preferred, but the ranking of indexed quantities and fixed quantity controls varies across countries. Those countries with a strong correlation between output and emissions and relatively low output variance favor indexed quantities, while those with low correlation and/or high output variance favor fixed quantities. Globally, indexed quantities outperform fixed quantity instruments.

Our motivation and application relate to cases where the government is seeking to regulate a market, constrained by both an information asymmetry (between the moment a policy is determined and the horizon over which it applies) and a limit on regulatory complexity. Similar features characterize other mechanism design problems where these results may be helpful. Sales contracts, for example, face an asymmetry of information between the moment a contract is agreed and when it is executed and, similarly, a limit to the complexity of contract contingencies. Like our regulatory example, subjecting delivery quantity and/or price to indexing rules can enhance contract performance (see, e.g., Li and Kouvelis (1999), Aase (2004), and Neuhoff and von Hirschhausen (2004)). In the case of monetary policy, the uncertain link between the instrument (current interest rate or money supply) and outcome (future inflation and output) mimics our information asymmetry. The literature on monetary policy considers ways to use all available information to improve performance but often ends up,

like our regulatory example, with fairly simple linear index rules to minimize squared errors (see Svensson (2003) for a recent summary). These examples suggest a potentially broad application of our analysis beyond the regulatory arena.

The remainder of the paper is organized as follows. First, we set up our model and review the original Weitzman (1974) result. Next, we introduce the notion of indexed quantities and derive results for both a general indexed quantity—where the mean quantity level and rate of adjustment to the index are distinct—as well as a simple proportional indexed quantity. Finally, we present an application to climate change and conclude.

2. Model and Analytic Results

Our modeling approach follows Weitzman (1974) with quadratic cost and benefit functions for a generic market, q . The functions can be viewed as local approximations about an arbitrary point. Maximizing net benefits based on these functions, we determine expected net benefits for optimal price and fixed quantity controls, as in Weitzman, and then for an indexed quantity policy. We consider two types of indexed policies, “ordinary” indexed quantities where the regulated quantity equals a fixed rate times the index, and “general” indexed quantities where the rate of adjustment is distinct from the mean level of control. We derive expressions for the difference in net benefits for pair-wise comparisons of the policies, evaluate the dependence of these policy rankings on key parameters, and summarize these rankings in a two-dimensional space defined by key parameter values.

2.1. Review of Prices versus Quantities

We start by replicating the basic Weitzman (1974) results with costs and benefits measured as quadratic functions about the expected optimal quantity q^* .⁵ Costs are given by

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

where θ_c is a mean-zero random shock to marginal costs with variance σ_c^2 , and the c_n parameters capture constant, linear, and quadratic behavior. We assume $c_2 > 0$; that is, costs are strictly convex. Note that we have defined the cost shock such that a positive value of θ_c reduces the marginal cost of *producing* q , but increases the marginal cost of *reducing* q . We chose this specification to ease the interpretation for our application to pollution control, where the regulator is typically seeking emission reductions.

Similar to costs, benefits are given by the form

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

with $b_2 \geq 0$; that is, benefits are weakly concave (marginal benefits are non-increasing). We ignore benefit uncertainty because, unless it is correlated with cost uncertainty, it does not affect net benefits in this quadratic setting (Weitzman 1974; Stavins 1996). The remaining parameters, particularly the linear terms, can be negative. This is relevant for our motivating example of pollution where marginal benefits are negative, and increasingly so, for increases in q .

Differentiating (1) and (2) with respect to q to obtain marginal costs and benefits, taking expectations, and equating the expressions, yields the condition

$$b_1 - b_2(q - q^*) = c_1 + c_2(q - q^*),$$

⁵ Like Weitzman, we make the approximation around the optimal fixed quantity q^* without loss of generality for the resulting comparative advantage expressions. A more general approximation simply adds constant terms to all of the expected net benefit expressions, which cancel out when they are compared.

for the optimal fixed quantity policy, a condition satisfied at $q = q^*$ if and only if $b_1 = c_1$. We now see the implication of our initial assumption that benefits and costs were approximated around the optimal fixed quantity policy, q^* . That is, $b_1 = c_1$; marginal benefits equal expected marginal costs at the optimum. Expected net benefits under the optimal fixed quantity policy, NB_Q , are given by

$$(3) \quad E[NB_Q] = b_0 - c_0.$$

An arbitrary price policy p equates marginal cost to price, ex post. That is, $p = c_1 - \theta_c + c_2(q - q^*)$, with an associated quantity response function of $q_p(\theta_c) = q^* + (p - c_1 + \theta_c)/c_2$. The optimal price policy, p^* , equates marginal benefits and expected marginal costs, given the response function $q_p(\theta_c)$. It is straightforward to show that

$$(4) \quad q_p^*(\theta_c) = q^* + \frac{\theta_c}{c_2},$$

with the implication that the optimal price equals the expected price at the optimal fixed quantity and yields the optimal fixed quantity in expectation. Expected net benefits under the optimal price policy, NB_P , are:

$$(5) \quad E[NB_P] = b_0 - c_0 + \frac{\sigma_c^2(c_2 - b_2)}{2c_2^2}.$$

Taking the difference between $E[NB_P]$ and $E[NB_Q]$ yields the familiar Weitzman (1974) relative advantage expression for prices versus fixed quantities:

$$(6) \quad \Delta_{P-Q} = \frac{\sigma_c^2(c_2 - b_2)}{2c_2^2}.$$

Prices outperform fixed quantities if the slope of marginal benefits is less than the slope of marginal costs, and vice versa.

At this point, it is useful to define both the first-best policy and the associated net benefits. Setting marginal costs equal to marginal benefits after the shock θ_c is revealed yields what we refer to as the optimal ex post quantity:

$$(7) \quad q_o(\theta_c) = q^* + \frac{\theta_c}{c_2 + b_2}.$$

Intuitively, the sum of the cost and benefit slopes $c_2 + b_2$ reflects the rate at which a deviation in quantities translates into a deviation in net benefits, where here the net benefit deviation equals θ_c . This in turn leads to an expected value for net benefits under the first-best policy, NB_o of

$$(8) \quad E[NB_o] = b_0 - c_0 + \frac{\sigma_c^2}{2(c_2 + b_2)}.$$

Graphically, we can visualize the outcomes under the first-best, price, and fixed quantity policies in Figure 1 for a particular realization of θ_c . The hatched area represents the loss under the fixed quantity policy and the shaded area represents the loss under the price policy, both relative to the first best. From the figure, we can see that while the price policy misses the optimum because it *over adjusts* the expected quantity target, the fixed quantity policy misses the optimum because it *fails to adjust at all* in response to the cost shock.

The divergence in performance of price and quantity controls from the optimum and from one another arises because of an information asymmetry. The regulator does not observe the cost shock θ_c that, in contrast, is known to the regulated firms at the time q is chosen. Once the information is revealed, it is not possible to rapidly adjust the policy, and we find that fixed policies lead to second-best outcomes with the well-known distinction between prices and quantities.

An important observation at this point is that an alternate policy could improve upon both fixed prices and quantities if somehow it adjusted the ex post quantity level in a way that was closer to the optimum than either of these instruments. In this regard, two things are immediately necessary: the adjustment should be correlated to the cost shock, the adjustment

should not be too small, and should especially not be too large.⁶ We now turn to how indexed quantities might achieve this end.

2.2. General Indexed Quantities

We consider a random variable, x , that is used to index the otherwise fixed quantity policy. In the pollution case, it is useful to think of x as some index of activity, such as output, that is correlated with the level of unregulated pollution. More generally, it could be anything related to the object of regulation, q , including weather or prices in related markets. We assume a linear policy of the form:

$$(9) \quad q(x) = a + rx,$$

where a and r are policy parameters, $E[x] = \bar{x}$, $\text{var}(x) = \sigma_x^2$, and $\text{cov}(x, \theta_c) = \sigma_{cx}$. That is, the index has mean \bar{x} , standard deviation σ_x , and covariance σ_{cx} with the cost shock θ_c .

As an example of an indexed quantity policy, the U.S. phasedown of lead in gasoline established rate limits in terms of grams of lead per gallon of gasoline, with the eventual quantity limit equaling the fixed rate times the volume of gasoline produced. The volume of gasoline represented an unknown, random variable to the regulator at the time of regulation, and introduced variation in the ex post quantity of lead released into the environment.

We consider two types of policies, a *general* indexed quantity (GIQ) policy where no restrictions are placed on the parameters a and r , and an *ordinary* indexed quantity (or just indexed quantity, IQ) policy where we constrain $a = 0$. In practice, the latter is the more common form of regulation where the regulated level of q is simply a multiple r of random variable x , as in the U.S. phasedown of lead in gasoline. Substituting the indexed quantity rule (9) into our benefit and cost expressions (1) and (2) and maximizing expected net benefits with

⁶ It is also necessary that information about the index become available alongside information about the shock. Learning about an index adjustment *after* firms have made their final decision about q is of little use.

respect to r and a first, and then only with respect to r while constraining $a = 0$, yields the optimal form of the GIQ and indexed quantity policies, respectively:

$$(10) \quad q_{GIQ}^*(x) = q^* + r^{**}(x - \bar{x}), \text{ and}$$

$$(11) \quad q_{IQ}^*(x) = r^* x,$$

where $r^{**} = (\sigma_{cx}/\sigma_x^2)/(b_2 + c_2)$, $r^* = (1 + v_x^2)^{-1}((q^*/\bar{x}) + v_x^2 r^{**})$, and $v_x = \sigma_x/\bar{x}$ (the coefficient of variation in x). For the remainder of this section, we focus on the GIQ policy, returning to discuss the ordinary indexed quantity policy in the next section.

The parameter r^{**} equals the coefficient of a regression of the first-best optimal adjustment ($\theta_c/(b_2 + c_2)$ from (7)) on x . Therefore, we can interpret the GIQ policy as the best linear predictor of the first-best adjustment, given x . If x and θ_c are jointly normal, the GIQ policy is also the minimum variance unbiased predictor (i.e., including the possibility of non-linear predictors). This result is easily extended to the case of multiple index variables, where x would be a vector of index variables and r^{**} would be a vector of regression coefficients.

Using expression (10) for the GIQ policy, we can derive expected net benefits equal to

$$(12) \quad E[NB_{GIQ}] = b_0 - c_0 + \frac{\sigma_c^2}{2(c_2 + b_2)} \rho_{cx}^2,$$

where $\rho_{cx} = \sigma_{cx}/(\sigma_x \sigma_c)$, the correlation of x and θ_c . Comparing this to the net benefits under the first-best policy given in (8), we can see that the GIQ policy achieves the first best if $\rho_{cx} = 1$, that is, if the index and cost shock are perfectly correlated. In other words, if we have an exogenous, observable index variable that perfectly reveals the cost shock, the information problem that creates our second-best setting vanishes and we can implement a first-best policy.

More generally, the gain from the GIQ policy will depend on the squared correlation, which can be interpreted as the goodness of fit (R^2) of a regression of the first-best optimal adjustment on the index. Thus, the degree to which the index can predict the underlying cost shock, in terms of predicted versus residual variation, determines the degree to which the

indexed policy achieves the first-best result given in (8). Meanwhile, the GIQ policy is always at least as good as the fixed quantity policy, with the relative advantage given by

$$(13) \quad \Delta_{GIQ-Q} = \frac{\sigma_c^2}{2(c_2 + b_2)} \rho_{cx}^2 \geq 0.$$

This expression is always non-negative and tends to zero as the correlation goes to zero. Similar observations about the ability of the GIQ policy to always perform better than fixed quantities are made by both Jotzo and Pezzey (2005) and Sue Wing et al. (2005).

Subtracting (5) from (12) yields the relative advantage of the GIQ policy over the price policy:

$$(14) \quad \Delta_{GIQ-P} = \frac{\sigma_c^2}{2(c_2 + b_2)} \left(\rho_{cx}^2 + \left(\frac{b_2}{c_2} \right)^2 - 1 \right).$$

The GIQ policy will therefore be preferred if benefits are sufficiently steep (as with a fixed quantity policy) *or* if correlation is high. Put another way, the preference for the GIQ policy versus prices is a competition between the relative flatness of marginal benefits (pushing Δ_{GIQ-P} negative) and correlation between the index and the cost shock (pushing Δ_{GIQ-P} positive).

Figure 2 shows the surplus diagram in Figure 1, but with the GIQ policy included (thickly outlined) for a case where it adjusts for roughly half of the observed cost shock. As indicated, the general indexed quantity policy will have an expected loss no larger than the quantity policy, but its advantage relative to the price policy hinges on the relative slopes and degree of correlation between the index and shock.

While not the focus of this paper, we note that a generalized indexed price (GIP) policy of the form $p_{GIP}^*(x) = p^* + u^{**}(x - \bar{x})$ is also possible, equaling the optimal fixed price policy plus an adjustment rate u^{**} times the deviation in the index from its expectation. As in the GIQ case, the optimal adjustment rate equals a regression coefficient, but this time for the optimal ex post *price* regressed on the index. Similar to the relative advantage of the GIQ policy over fixed

quantities, the relative advantage of the GIP policy over fixed prices equals the difference between the first-best welfare gain and the fixed price policy, times the correlation squared, $\Delta_{GIP-P} = 1/2 \left(\sigma_c^2 / (c_2 + b_2) \right) (b_2 / c_2)^2 \rho_{cx}^2$. As the correlation goes to unity, the GIP policy achieves the first-best outcome; as it tends to zero, it becomes the same as the fixed price policy.

While it is easy to imagine general indexed quantities of the form (9), or even the general indexed prices noted above, in practice we see very few—much as we see very few price-quantity hybrid policies along the lines of Roberts and Spence (1976) or Pizer (2002). For that reason, we now focus on the ordinary indexed quantity policies given by (11).

2.3. (Ordinary) Indexed Quantities

Consider the more common case in practice where the regulated quantity is strictly equal to a rate times the index variable,

$$q_{IQ}(x) = r x,$$

where we have imposed the constraint that $a = 0$ in (9). We noted above that the optimal indexed quantity rate is

$$(15) \quad r^* = \frac{(q^*/\bar{x}) + v_x^2 r^{**}}{1 + v_x^2}.$$

Like the optimal rate for the GIQ policy (r^{**}), the optimal indexed quantity rate r^* can be interpreted as a regression coefficient when the first-best adjustment $\theta_c / (c_2 + b_2)$ is regressed on x —but this time with the constraint that a constant term is not included—a point we return to below.

Expression (15) for r^* is a weighted average of two terms, q^*/\bar{x} and r^{**} , with the relative weight depending on the coefficient of variation of x . As the index variation becomes large, r^* tends to the GIQ regression coefficient r^{**} and the *variance* of the IQ and GIQ policies converge. As variation in the index tends to zero, r^* tends to q^*/\bar{x} , and the *mean* of the IQ and GIQ (and fixed quantity) policies converge. Because r^* cannot simultaneously match both the mean and

variance of the GIQ policy (unless it happens that $a = 0$ even when unconstrained), (15) represents the minimum variance solution given that there is only one rather than two flexible parameters. An implication, nonetheless, is that r^* does not generally yield q^* in expectation, as do the other policies, although it will be quite close in typical applications where v_x is small.

Using (15), we can derive the expected net benefits of the optimal indexed quantity,

$$(16) \quad E[NB_{IQ}] = b_0 - c_0 - \frac{b_2 + c_2}{2} \frac{(q^*/\bar{x})^2}{1 + v_x^2} \sigma_x^2 + \frac{\sigma_c^2}{2(b_2 + c_2)} \frac{2(v_{q^*}^2/v_x) + v_x^2 \rho_{cx}}{1 + v_x^2} \rho_{cx}$$

where we have defined $v_x = \sigma_x/\bar{x}$ and

$$(17) \quad v_{q^*} = (\sigma_c/(b_2 + c_2))/q^*,$$

the coefficient of variation in the index and the ex post optimal quantity from (7), respectively.

Arranged this way, the expression (16) highlights two important results. First, if there is no correlation between the index and the cost shock, the last term vanishes and variance in the index reduces expected net benefits based on the third term. This follows from Jensen's inequality applied to the fact that net benefits (costs minus benefits) are a concave function of the regulated quantity level, and that higher variance in the index implies higher variance in the indexed quantity level and lower expected net benefits. Second, for a given index variance, e.g., holding the third term constant, correlation between the index and cost shock improves net benefits based on the fourth term.

If $\rho_{cx} \neq 0$, it is useful to rearrange (16) to yield,

$$(18) \quad E[NB_{IQ}] = b_0 - c_0 + \frac{\sigma_c^2}{2(c_2 + b_2)} \rho_{cx}^2 \left(1 - \frac{1}{1 + v_x^2} \left(1 - \frac{v_x}{\rho_{cx} v_{q^*}} \right)^2 \right),$$

Note that $v_x/(\rho_{cx} v_{q^*}) = (q^*/\bar{x})/r^{**}$, the ratio of the two terms being averaged to determine the index rate in (15).

Comparing (12) and (18), we can see that the net benefit expression for ordinary indexed quantities is the same as for the GIQ policy, except that it contains an extra factor multiplying the third term. Holding other parameters fixed, increases in v_x improve the performance of indexed quantities up to the point where

$$(19) \quad \frac{v_x}{\rho_{cx} v_{q^*}} = 1,$$

beyond which further increases in v_x worsen the performance of indexed quantities. When this condition is exactly met, the term in (outer) parentheses of (18) equals one and the expected welfare gain from the indexed quantity policy equals the expected gain from the GIQ policy.

How do we interpret the condition given in (19)? One way is to recall, as noted above, that $v_x / (\rho_{cx} v_{q^*}) = (q^* / \bar{x}) / r^{**}$, yielding the condition $(q^* / \bar{x}) / r^{**} = 1$ and, therefore, $r^* = r^{**}$ from the definition of r^* in (15). That is, the rate of adjustment is the same under the indexed quantity policy and the GIQ policy. As noted above, both r^{**} and r^* are regression coefficients in models predicting the first-best adjustment as a function of x , the former with a constant and the latter without.⁷ If the two regression coefficients happen to be equal thanks to a lucky or thoughtful choice of the index variable, it also implies the freely estimated constant a in the GIQ policy equals zero, the indexed quantity yields the same response function $q(x)$ as the GIQ policy, and it performs just as well. However, as $(q^* / \bar{x}) / r^{**}$ diverges from unity, r^* diverges from r^{**} . This divergence reflects an increased importance of the non-zero constant term in the regression model, and the ordinary indexed policy does increasingly worse than the more flexible GIQ policy.

⁷ In general, a regression coefficient with and without a constant will be the same if the coefficient of variation of the explanatory variable equals the dependent variable's coefficient of variation, times the correlation between the variables—exactly the condition in (19).

As an alternative interpretation of (18) and the resulting condition (19), we can think about the “desired” value of v_x for an indexed quantity policy, given the values of v_{q^*} and the correlation ρ_{cx} . How much variation should there be in the index in order to maximize net benefits? If an index’s correlation with the underlying cost shock is perfect, it makes sense to have the index vary by just as much as the ex post optimal quantity (i.e., $v_x = v_{q^*}$). At the other extreme, when the correlation is zero, it is preferable to have an index with no variation because the index is all noise with respect to the cost shock and optimal quantity. Likewise, for cases between these two extremes, expression (19) reveals that as the correlation declines the desired variation in the index should also decline.

As the level of index variation deviates from the desired level, the performance of the indexed quantity policy deteriorates. In particular, very noisy indexes will tend to a limiting net benefit given by

$$\lim_{v_x \rightarrow \infty} E[NB_{IQ}] = b_0 - c_0 + \frac{\sigma_c^2}{2(c_2 + b_2)} \rho_{cx}^2 \left(1 - \left(\frac{1}{\rho_{cx} v_{q^*}} \right)^2 \right).$$

Indexes with too small a coefficient of variation, at worse, tend toward the fixed quantity result, a point we now confirm.

2.4. The Advantage of Indexed Quantities Relative to Prices and Quantities

We can now calculate the relative advantage of indexed quantities to prices and fixed quantities. The relative advantage of indexed quantities over fixed quantities is:

$$(20) \quad \Delta_{IQ-Q} = \frac{\sigma_c^2}{2(c_2 + b_2)} \rho_{cx}^2 \left(1 - \frac{1}{1 + v_x^2} \left(1 - \frac{v_x}{\rho_{cx} v_{q^*}} \right)^2 \right).$$

In terms of the parameter v_x , this expression equals zero when v_x equals zero, reaches a maximum of Δ_{GIQ-Q} when $v_x = \rho_{cx} v_{q^*}$, and then declines to $\Delta_{GIQ-Q} \left(1 - (\rho_{cx} v_{q^*})^{-2} \right)$ as $v_x \rightarrow \infty$.

Based on these tendencies, if $\rho_{cx} v_{q^*} \geq 1$ this expression is non-negative for all values of v_x and indexed quantities are always at least as good as, and usually better than, fixed quantities.

In all practical cases, however, $\rho_{cx} v_{q^*} < 1$, because $\rho_{cx} \leq 1$ by definition and $v_{q^*} < 1$ unless the first-best optimum is highly variable relative to its mean—an unusual case that would in any event be inappropriate for the modeling framework we have set out. With $\rho_{cx} v_{q^*} < 1$, indexing is preferred to fixed quantities so long as $v_x / (\rho_{cx} v_{q^*}) < 2 / (1 - (\rho_{cx} v_{q^*})^2)$. We can simplify this condition by further focusing on cases where the variation is not only less than one, but relatively small (i.e., $v_{q^*} \ll 1$), which leads to the approximate condition $v_x / (\rho_{cx} v_{q^*}) < 2$ for indexed quantities to be preferred. Such a focus is already implicit given the framing of our problem as a local quadratic approximation around the expected optimum, and likewise seems reasonable for practical targets of regulation.

The intuition for this latter condition is straightforward to understand. We previously observed that for parameter values satisfying $v_x / (\rho_{cx} v_{q^*}) = 1$ the indexed quantity matches the GIQ policy. That is, the expression can be re-written as $(q^* / \bar{x}) / r^{**} = 1$ and the indexed quantity rate of adjustment r^* equals the GIQ rate of adjustment r^{**} based on (15). Now imagine parameter values whereby $v_x / (\rho_{cx} v_{q^*}) = (q^* / \bar{x}) / r^{**} = 2$, corresponding to the threshold condition for preferences between indexed and fixed quantities to flip. Under the noted assumption $v_{q^*} \ll 1$, we know $v_x \ll 1$ over the relevant range near v_{q^*} and therefore $r^* \approx q^* / \bar{x}$ based on (15). Under this assumption, the adjustment based on this rate is approximately double what it should be compared to the GIQ policy (i.e., $r^* / r^{**} \approx 2$) and all the expected gains relative to the fixed quantity policy are squandered by overshooting the new expected optimum, as shown in Figure 3. The surprisingly simple result that the point of indifference between indexing and fixed quantities occurs at $r^* / r^{**} \approx 2$ is attributable to the linear marginal form assumptions, which

imply that equal-sized positive and negative deviations from the optimum have equal and opposite effects on marginal net benefits.⁸

When v_{q^*} and v_x are closer to one, r^* is an average of q^*/\bar{x} and r^{**} based on (15), reflecting the fact that we are willing to trade off higher mean error to better match variance and reduce the mean-squared error. Therefore, $v_x/(\rho_{cx}v_{q^*})$ can actually be slightly larger than 2 before indexed quantities squander their gain over fixed quantities. Specifically, for values of $2/\left(1-(\rho_{cx}v_{q^*})^2\right)$ or smaller, indexed quantities continue to be preferred.

What about prices? The relative advantage of indexed quantities over prices is given by:

$$(21) \quad \Delta_{IQ-P} = \frac{\sigma_c^2}{2(c_2 + b_2)} \left(\left(\frac{b_2}{c_2} \right)^2 - 1 + \rho_{cx}^2 \left(1 - \frac{1}{1+v_x^2} \left(1 - \frac{v_x}{\rho_{cx}v_{q^*}} \right)^2 \right) \right).$$

Based on the expression in outer parentheses, the sign of Δ_{IQ-P} is positive or negative depending on whether $(b_2/c_2)^2$ is greater or less than $1 - \rho_{cx}^2 \left(1 - (1+v_x^2)^{-1} \left(1 - (v_x/(\rho_{cx}v_{q^*})) \right)^2 \right)$. The expression can be viewed as a parabola-like function in $v_x/(\rho_{cx}v_{q^*})$, with a maximum at $v_x/(\rho_{cx}v_{q^*}) = 1$, where it equals $(b_2/c_2)^2 - 1 + \rho_{cx}^2$ and where $\Delta_{IQ-P} = \Delta_{GIQ-P}$ (matching the general indexed quantity policy comparison). Thus indexed quantities are preferred to prices when marginal benefits are relatively steep and/or when correlation with the index is high, as was the case comparing the GIQ policy to prices.

As $v_x/(\rho_{cx}v_{q^*})$ deviates from 1, the relative performance of the indexed quantity policy worsens and the expression in outer parentheses of (21) tends to

$(b_2/c_2)^2 - 1 + \rho_{cx}^2 \left(1 - (1/\rho_{cx}v_{q^*})^2 \right)$ for values of $v_x \rightarrow \infty$ (treating $\rho_{cx}v_{q^*}$ as fixed) and equals $(b_2/c_2)^2 - 1$ when $v_x = 0$. Whether indexed quantities prevail over prices depends on the degree

⁸ Note that if marginal costs are convex the critical value would be more than 2; conversely, if marginal benefits are convex the critical value would be less than 2.

of correlation between the index and cost shock and/or steepness of marginal benefits, as well as whether $v_x/(\rho_{cx}v_{q^*})$ is sufficiently close to 1.

2.5. Summary of the Relative Advantages of Alternate Policies

We can summarize the relative advantages of indexed quantities, prices, and fixed quantities, in a two-dimensional space. The space is defined by the squared ratio of marginal benefit / cost slopes along the y -axis, and the expression $v_x/(\rho_{cx}v_{q^*})$, measuring how closely indexed quantities match the GIQ policy, along the x -axis. Figure 4 shows each relative advantage relationship separately. In the top panel, we show a horizontal line where $(b_2/c_2)^2 = 1$. Above this line, fixed quantities are preferred to prices and below it prices are preferred to fixed quantities—this is the Weitzman (1974) result.

In the middle panel we show a vertical line at $v_x/(\rho_{cx}v_{q^*}) = 2/\left(1 - (\rho_{cx}v_{q^*})^2\right) \approx 2$ based on (20). For cases where $v_x/(\rho_{cx}v_{q^*}) < 2/\left(1 - (\rho_{cx}v_{q^*})^2\right)$ indexed quantities are preferred to fixed quantities; for the reverse, fixed quantities are preferred. The rough intuition for the fixed versus indexed quantity result is that indexed quantities are an improvement *unless* they adjust by more than about twice the desired amount conditional on x —with the desired amount arising where $v_x/(\rho_{cx}v_{q^*}) = 1$ (i.e., where indexed quantities replicate the GIQ policy).

Finally, the bottom panel shows the nearly parabolic function defined by (21) describing the boundary between a preference for prices over indexed quantities (below the curve) and a preference for indexed quantities over prices (above the curve). Here, losses relative to the first-best outcome under the price policy depend on the distance from the x -axis—the ratio $(b_2/c_2)^2$ —with relatively steep marginal benefits disfavoring prices. Meanwhile, losses under indexed quantities depend on a more complex relationship involving both the correlation between index and the cost shock (ρ_{cx}) and the difference between $v_x/(\rho_{cx}v_{q^*})$ and its most favorable value of 1—with high values of ρ_{cx}^2 and values of $v_x/(\rho_{cx}v_{q^*})$ close to 1 favoring indexed quantities. The locus of points where these losses are equivalent, and where prices and indexed quantities generate the same expected net benefits, defines the parabola-like function

shown in the figure, passing through the points $(0,1)$, $(1,1-\rho_{cx}^2)$, and (approximately) $(2,1)$. Inside this parabola, $(b_2/c_2)^2$ is sufficiently large and $v_x/(\rho_{cx}v_{q^*})$ is sufficiently close to 1 to favor indexed quantities. Note that the effect of ρ_{cx} on the policy comparison arises from both its scaling of $v_x/(\rho_{cx}v_{q^*})$ and its movement of the minimum of the parabola at $1-\rho_{cx}^2$. Based on (5) and particularly (16), however, we know that the unambiguous effect of higher values of ρ_{cx} (other things equal) is to tilt preferences towards indexed quantities.

Figure 5 shows these relations together, distinguishing six regions where different policy rankings occur. Note that for the GIQ policy, we can look along a vertical line where $v_x/(\rho_{cx}v_{q^*})=1$ to determine policy rankings. In that case, when $(b_2/c_2)^2 < 1-\rho_{cx}^2$, we have prices preferred to general indexed quantities preferred to quantities. When $1 > (b_2/c_2)^2 > 1-\rho_{cx}^2$, general indexed quantities are preferred to prices are preferred to quantities. Finally, when $(b_2/c_2)^2 > 1$, indexed quantities are preferred to quantities are preferred to prices. In no instance is the fixed quantity policy preferred to index policies when $v_x/(\rho_{cx}v_{q^*})=1$, as indexed quantities match the performance of the GIQ policy, and the GIQ policy is always (weakly) preferred to fixed quantities.

Given five parameters—the marginal cost and benefit slopes, the coefficients of variation for the index and ex post optimal quantity, and the correlation between the latter two—we can identify a point in Figure 5 and determine the relative ranking of policies. We now consider an application of this approach to the case of climate change policy in a cross section of countries.

3. An Application to Environmental Policy

In our application to climate change, we compare carbon dioxide (CO₂) mitigation policies based on either fixing the price of emissions, the quantity of emissions, or the ratio of emissions to GDP (emissions intensity). We also present results for the general indexed quantity policy, even though such policies have not yet received serious consideration in national or international policy deliberations. Based on the results in section 2, the necessary parameters for

understanding the relative advantage of these policies, given by equations (6), (13), (14), (20), and (21), are the marginal cost and benefit slopes (c_2 and b_2), the variance of the cost shock (σ_c^2), the coefficients of variation of the index and ex post optimal quantity (v_x and v_{q^*}), and the correlation of the cost shocks and the index (ρ_{cx}).

In the remainder of this section, we first present a useful decomposition of the cost shock, then describe how we obtained the necessary parameter values, and finally present the resulting empirical results for a cross section of countries.

3.1. Decomposition of Cost Shocks

We begin by noting that a key feature of the problem, the cost shock, is more easily considered in two pieces, one owing to uncertainty about the cost of the production technology for shifting the regulated quantity away from its baseline level (θ_m), and one owing to uncertainty about the baseline level itself (θ_q) (Newell and Pizer 2003):

$$(22) \quad \theta_c = \theta_m + c_2 \theta_q.$$

Note that if the baseline shifts by θ_q , it is equivalent to a $c_2 \theta_q$ shift in marginal costs of achieving a particular quantity. The slope of the marginal cost function, c_2 , converts horizontal shocks into vertical shocks. Based on this decomposition, and assuming the two parts are uncorrelated, we have

$$(23) \quad \sigma_c^2 = \sigma_m^2 + c_2^2 \sigma_q^2,$$

Where σ_m^2 and σ_q^2 are the variances of θ_m and θ_q , respectively.

There are two other places in the relative advantage expressions where this decomposition is relevant. The first is where ρ_{cx} appears in expressions involving the index. Assuming the index is correlated with the baseline quantity level, but not the technology cost, this parameter can be re-expressed as

$$(24) \quad \rho_{cx} = \frac{\sigma_{cx}}{\sigma_c \sigma_x} = \frac{c_2 \sigma_{qx}}{\sigma_c \sigma_x} = \frac{c_2 \sigma_q \rho_{qx}}{\sqrt{\sigma_m^2 + c_2^2 \sigma_q^2}} = \frac{\rho_{qx}}{\sqrt{1 + (\sigma_m / c_2 \sigma_q)^2}},$$

where σ_{qx} is the covariance and ρ_{qx} the correlation between the baseline component of the cost shock and the index. The last expression reflects the fact that the correlation between the cost shock and index now equals the correlation of the baseline quantity and the index, diminished by a factor of $\sqrt{1 + (\sigma_m / c_2 \sigma_q)^2}$ measuring the relative importance of the uncorrelated component σ_m . When the uncorrelated component is relatively small then ρ_{cx} will tend toward ρ_{qx} . When the reverse is true, and the variance of the uncorrelated piece is relative large then ρ_{cx} will tend toward 0.

The second place where the decomposition is relevant is where v_{q^*} appears in expressions involving the indexed quantity policy. Using (17) and (23), v_{q^*} can be rewritten as

$$(25) \quad v_{q^*} = v_{\bar{q}} \left(\frac{\bar{q}}{q^*} \right) \sqrt{\left(\frac{c_2}{b_2 + c_2} \right)^2 + \left(\frac{\sigma_m}{(b_2 + c_2) \sigma_q} \right)^2},$$

where $v_{\bar{q}} = \sigma_q / \bar{q}$ is the coefficient of variation in the baseline quantity. Similar to (24), the coefficient of variation of the ex post optimal quantity equals the coefficient of variation of the baseline quantity, increased by a factor measuring the relative importance of the uncorrelated component σ_m as well as the ratio \bar{q} / q^* (the latter correcting for the difference in means between $v_{\bar{q}}$ and v_{q^*}).

We now turn to finding values for these and the remaining parameters.

3.2. Climate Change Policy Parameters

For all of the climate change parameters that are independent of national data on emissions and output, we follow the approach in Newell and Pizer (2003), updating the values to 2004 values. For the slope of the marginal benefit function for CO₂ reduction, b_2 , we assume

$b_2 = 9.2 \times 10^{-13}$ \$/ton².⁹ In order to determine q^*/\bar{q} , we also use their definition of mitigation benefits to estimate a current level of marginal benefits of 2.4 \$/ton—within rounding error of the value reported in Nordhaus (1994).¹⁰ Note that given the value of b_2 and emission levels on the order of billions (10^9) of tons for the largest countries, this marginal benefit estimate is nearly constant over the range of possible emission levels.¹¹

Based on results from 10 models that participated in the Energy Modeling Forum's EMF 16 (Weyant and Hill 1999), Newell and Pizer estimated that each 1% reduction in CO₂ raises marginal costs by 1.2 \$/ton globally, with a standard deviation of 1.1 \$/ton associated with a 1% reduction. In order to translate this marginal cost slope described in \$/ton per percentage point terms into \$/ton² terms, we divide by one percent of the baseline emission level in the relevant region (i.e., $c_2 = 1.1/(0.01\bar{q})$). This results in a range of marginal cost slopes across countries (discussed below) from $c_2 = 2.0 \times 10^{-8}$ \$/ton² to $c_2 = 4.5 \times 10^{-7}$ \$/ton².¹² In addition, σ_m is set at 1.1 \$/ton based on the standard deviation of marginal control costs across these models. Finally, from the earlier marginal benefit estimate of 2.4 \$/ton, we determine that the optimal fixed quantity reduction, matching expected marginal cost to marginal benefit, is 2.1% and thus $q^*/\bar{q} = 0.979$. Table 1 summarizes the values for all parameters that are common across geographic regions.

⁹ Because CO₂ is a highly persistent stock pollutant, the marginal benefit of reducing CO₂ emissions reflects the discounted flow of reduced climate damages, which depreciate over time.

¹⁰ Nordhaus reports a value of \$6.77 per ton carbon in 2005 (Table 5.7). Adjusting for inflation and converting to tons of CO₂ yields 2.44 \$/ton.

¹¹ That is, 9.2×10^{-13} \$/ton² multiplied by some number of 10^9 tons is a negligible adjustment to 2.4 \$/ton.

¹² This approach implicitly assumes that the production technology for CO₂ reduction is identical and scalable across countries. While this is of course not strictly true, we think this yields a reasonable benchmark value for each country. Furthermore, we found that changing c_2 or σ_m by an order of magnitude in either direction did not change the resulting policy rankings discussed below.

3.3. Country-level Emissions and GDP Data

The remaining variables necessary for the relative advantage expressions are \bar{q} , $v_{\bar{q}}$, v_x , and ρ_{qx} . For these estimates, we focus on 19 countries that in 2002 contributed at least 1% to global CO₂ emissions, as well as the world as a whole.¹³ The policies implicitly being modeled are therefore economy-wide policies at the national and global levels. We also consider the U.S. electricity sector by itself, with an implicit sectoral-level policy. Table 2 gives the 2002 emissions, GDP, and emissions intensity for these countries, with the United States, China, Japan, and India being the largest emitters, at 23%, 14%, 5%, and 4% of global emissions respectively.¹⁴ We use these 2002 values for emissions to approximate \bar{q} , and report country-specific values of c_2 in the last column of Table 2, where $c_2 = 1.1/(0.01\bar{q})$ as explained above.

To estimate values for $v_{\bar{q}}$, v_x , and ρ_{qx} , we posit a simple vector forecasting model for emissions and output,

$$(26) \quad \begin{pmatrix} \ln q_t \\ \ln x_t \end{pmatrix} - \begin{pmatrix} \ln q_{t-1} \\ \ln x_{t-1} \end{pmatrix} = \begin{pmatrix} g_q \\ g_x \end{pmatrix} + \begin{pmatrix} \varepsilon_{1t} \\ \varepsilon_{2t} \end{pmatrix},$$

where g_q and g_x are annual growth rates in emissions and output, and the ε_t 's are errors. Defined this way, and fixing policies for one period, $v_{\bar{q}}$ is the standard deviation of the first error, v_x is the standard deviation of the second, and ρ_{qx} is their covariance.¹⁵ We apply this model to country-level data over the period 1980-2002 on the quantity of CO₂ emissions from the consumption and flaring of fossil fuels, and economic output as measured by gross domestic product (Energy Information Administration 2004). With these estimates of $v_{\bar{q}}$, v_x , and ρ_{qx} ,

¹³ We do not include Russia, Ukraine, and Germany because these countries went through major transitions in the last two decades, making their emissions and economic output data either unreliable or unavailable.

¹⁴ Russia, which is not included here, accounts for 6% of the world total.

¹⁵ Because a small deviation in logs approximates the underlying deviation in levels, divided by the expected level, modeling in logs has the convenient effect of converting standard deviations into coefficients of variation and covariance into correlation (as long as the deviations are small).

equations (23), (24), and (25) allow us to compute σ_c , ρ_{cx} , and v_{q^*} , as well as the expression $v_x/(\rho_{cx}v_{q^*})$ summarizing the degree to which the indexed quantity policy matches the GIQ policy. The results of these calculations are shown in Table 3.¹⁶

Differences among countries are significant. The coefficient of variation in emission predictions ranges from a low of 2.4% in the United States to a high of 7.2% in Poland, while the coefficient of variation in the output forecast ranges from a low of 1.4% in Italy to a high of 6.8% in Poland. The resulting values of σ_c —including variation due to uncertainty in both baseline emissions and the cost of achieving a given reduction level—ranges from about 3-8 \$/ton across the countries. Note that the values for the world as a whole are slightly lower, reflecting the tendency of idiosyncratic shocks in different countries to average out. The values for the electricity sector in the U.S. tend to be quite similar to the U.S. as whole, reflecting that sector's important role in both emissions and economic activity.

The degree of correlation in baseline emissions and output (ρ_{qx}) also varies widely across countries, from 0.10 in France, which obtains a large fraction of its electricity from nuclear, to 0.74 in China, which is heavily reliant on fossil fuels. The correlation is 0.70 for the United States as a whole and 0.84 for the U.S. electricity sector. Higher degrees of correlation indicate situations where indexed quantities have the potential to perform well.

Estimates of $v_x/(\rho_{cx}v_{q^*})$ are presented in the last column of Table 3, measuring the deviation of the indexed quantity policy from the GIQ policy. Other things equal, this expression is larger for countries with relatively high output variation or low correlation between output and emissions. Noting that indexed quantities perform best when this expression equals unity, we see that output variation is rarely too small (only for Korea). However, output variation is large enough to cause a preference for quantities over indexed quantities for about

¹⁶ We do not report values of ρ_{cx} , and v_{q^*} . Noting that $b_2 \approx 0$, $\bar{q}/q^* \approx 1$, and σ_m is relatively small, we know $\rho_{cx} \approx \rho_{qx}$ and $v_{q^*} \approx v_{\bar{q}}$.

half the countries, including Japan, France, Australia, and others, a point we now consider in more detail.¹⁷

3.4. The Relative Advantage of Alternate Climate Policies

Taking the necessary parameter values from Table 1 through Table 3, and using (6), (13), (14), (20), and (21) to compute the relative advantage among various combinations of policies, Table 4 shows the results of this comparison for a one-year policy.¹⁸ Given the flatness of the marginal benefit function relative to the marginal cost function, the results reconfirm the universal preference for price policies over either fixed or indexed quantity policies (Newell and Pizer 2003). That is, all the results for Δ_{P-Q} are positive and for Δ_{IQ-P} and Δ_{GIQ-P} are negative. We also confirm the result from (13), that the GIQ policy is always weakly preferred to the fixed quantity policy so that $\Delta_{GIQ-Q} \geq 0$. Finally, we note that for cases where the parameters in Table 3 are relatively similar—for example, the U.S. electricity sector and the United States as a whole—the values in Table 4 will be proportional, being scaled by the level of baseline emissions in Table 2.¹⁹

The interesting calculation from the perspective of both theory and practice is the relative advantage ranking of indexed quantities over fixed quantities. From the aforementioned observations, it is the only comparison where the direction is unclear for climate policy. This comparison is also an important dimension of the climate change policy debate between the United States and the European Union. We see that this ranking varies across countries in direct

¹⁷ Pizer (2005) compared the coefficient of variation in intensity and emissions to provide a crude argument in favor of targets based on one or the other. It can be shown that such a comparison is equivalent to comparing $v_x / (\rho_{qx} v_q)$ to 2 only if emissions and output have roughly the same coefficient of variation.

¹⁸ See Newell and Pizer (2003) for a discussion of policies that last multiple periods; for simplicity, we focus on a policy lasting a single period.

¹⁹ That is, the U.S. electricity sector comprises about 40% of U.S. emissions. Consequently, given approximately the same values in Table 3, the relative advantage values for the U.S. electricity sector in Table 4 are about 40% of the U.S. values.

correspondence with the extent to which the ratio in the last column of Table 3 is greater than or less than 2. When $v_x / (\rho_{cx} v_{q^*}) > 2$ because the coefficient of variation in output is relatively high compared to that of the ex post optimal emissions level, or their correlation is low, fixed quantities are preferred to quantities indexed by output.

For about half the countries, including the two biggest emitters—the United States and China—indexed quantities yield higher expected net benefits than fixed quantities. For the other half, including the third and fourth biggest emitters examined—Japan and India—as well as the United Kingdom and France, fixed quantities dominate indexed quantities. At a global level, indexed quantities dominate. Most of the countries where indexing has a negative effect on net benefits have correlations of less than 0.25. The exceptions are Indonesia, Iran, Poland, and Saudi Arabia, which all have unusually high degrees of variation (above 4.5%) in economic output—to an extent where the disadvantage of high output variation outweighs the advantage of correlation.

In countries where $v_x / (\rho_{cx} v_{q^*})$ is close to unity, including Brazil, Italy, Korea, Netherlands, Spain, and the United States, the indexed quantity policy is close to the GIQ policy and the third and fourth columns are similar if not identical in Table 4. That is, Δ_{GIQ-Q} is equal to or very close to Δ_{IQ-Q} (and the same for the comparison to price policies). As we have repeatedly emphasized, the key for indexed quantities is whether the index possesses just the right amount of variation, given the variation in the ex post optimum and their correlation. As noted above, the results in Table 4 also demonstrate the unambiguous dominance of the GIQ policy over ordinary indexing. The advantage of the GIQ policy over ordinary indexing is greatest when the index has the wrong amount of variation (e.g., Indonesia, Iran, Poland, and Saudi Arabia noted above). Moderating the degree to which these output fluctuations influence the index without upsetting the mean outcome is particularly advantageous.

4. Conclusions

The relevance and importance of instrument choice for policy design has never been greater, particularly in the realm of environmental policy. With the increasing acceptance in policy circles of market-based instruments, especially tradable permits, attention has turned to the more subtle design elements of these instruments and how they might be refined. In addition, interest has risen in the properties of more traditional instruments, such as performance standards, when flexibility is introduced through trading (e.g., potential CAFE reforms in the United States). With the European Union and the United States currently on opposite sides of a debate over fixed versus indexed quantity policies, this interest is particularly intense in the realm of climate change. Such interest arises both in relation to the form that national commitments might take within an international framework, and in the design of domestic implementing policies.

Our paper contributes to this debate by clarifying analytically how uncertainty in the costs of meeting particular policy targets might or might not be ameliorated by indexing fixed quantity policies to variables such as economic output. We find that the advantage of such indexing depends on a tradeoff between the introduction of an additional source of uncertainty—which lowers expected net benefits—and the benefit-raising effect of adjusting the policy target ex post thanks to correlation of the index with the object of regulation. For typical cases where uncertainty is relatively small (variation in the ex post optimum of less than 10% of its mean), the preference for indexed over fixed quantities reduces to a question of whether the ratio of coefficients of variation of the index and the ex post optimal quantity, divided by their correlation, is less than two. This is fundamentally an empirical question for ordinary indexed quantity policies, where the quantity is strictly proportional to the index. A general indexed quantity policy, however, allows separate setting of the mean quantity level and rate of adjustment to the index, and such a policy will always dominate a fixed quantity policy from the perspective of maximizing expected net benefits. Comparisons to a price policy are more complex and involve the ratio of the slopes of marginal benefits and costs.

These conclusions are subject to the caveat that we have chosen a deliberately simple model to focus in on what we believe to be one of the most important elements of the instrument

choice question, namely cost uncertainty. We have abstracted from other relevant concerns, including the potential for an indexed quantity policy to create undesirable incentives if firms perceive that they can gain additional emission rights by increasing their output.²⁰ While we do not think this is a concern for national-level policies, it could be for indexed policies at the sectoral or product level. We have also not addressed the fact that quantities indexed to output, even if they reduce overall expected costs, may lead to worse outcomes when output is low and better outcomes when output is high. This type of pro-cyclical behavior may be undesirable from a macroeconomic perspective, although we suspect this concern is not large.²¹

Applying these conceptual insights and analytic formulae to the case of climate change policy across the biggest international emitters of CO₂, we find that prices (i.e., carbon taxes) universally dominate both fixed and indexed quantities (i.e., tradable permits) from an efficiency perspective—reconfirming previous research. More interestingly, indexing quantities to economic output yields higher expected net benefits than fixed quantity policies for about half the countries we assessed, including the United States and China, as well as for the world taken as a whole. A more general indexed quantity policy, where the mean quantity level and rate of adjustment are distinct, can deliver significant gains relative to ordinary indexing for countries that have unusually high variance in economic output, such as Indonesia, Iran, Poland, and Saudi Arabia.

Further work is needed to consider more accurate representations of costs, benefits, policies, and uncertainty, and to address the robustness of these results. However, these results do indicate that alternate policies work better in different circumstances and that an international system that aspires to global efficiency through domestic policies may need to accommodate these differences.

²⁰ This is the typical form of a performance standard, such as the U.S. lead phasedown in gasoline. Alternatively, emission rights could be increased for all firms based on aggregate output, diluting the effect. See Fischer (2003) for a discussion of these issues.

²¹ This point is discussed in Ellerman and Sue Wing (2003).

Figures and Tables

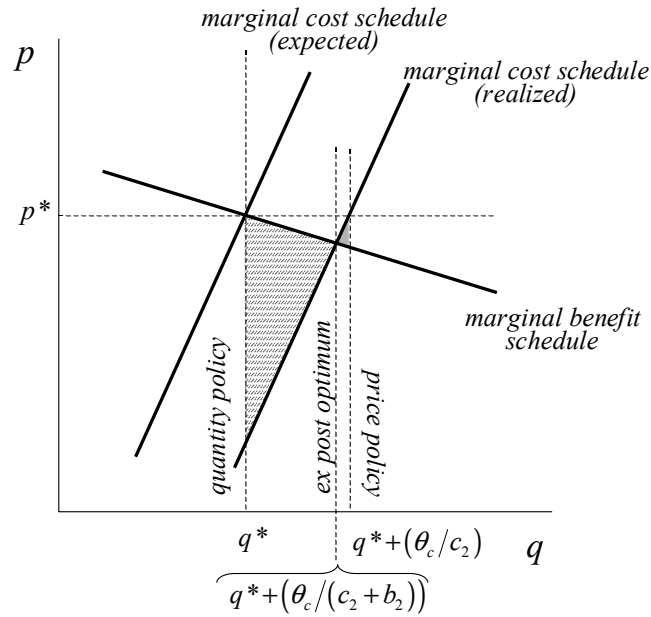


Figure 1. Welfare losses of prices and quantities relative to optimum (quantity loss is hatched; price loss is shaded)

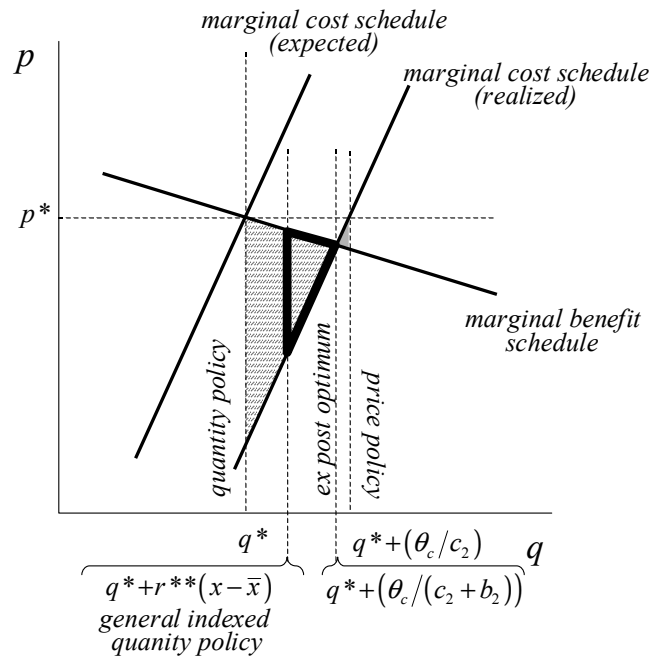


Figure 2: Welfare losses under quantity, price, and general indexed quantity policies (quantity loss is hatched; price loss is shaded; indexed quantity loss thickly outlined)

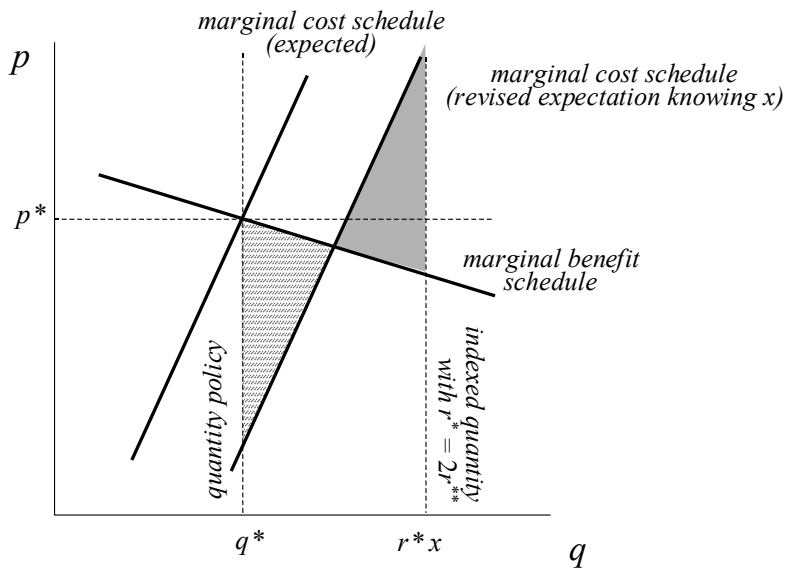


Figure 3. Welfare losses under quantity and indexed quantity policies (quantity loss is hatched; indexed quantity loss is shaded)

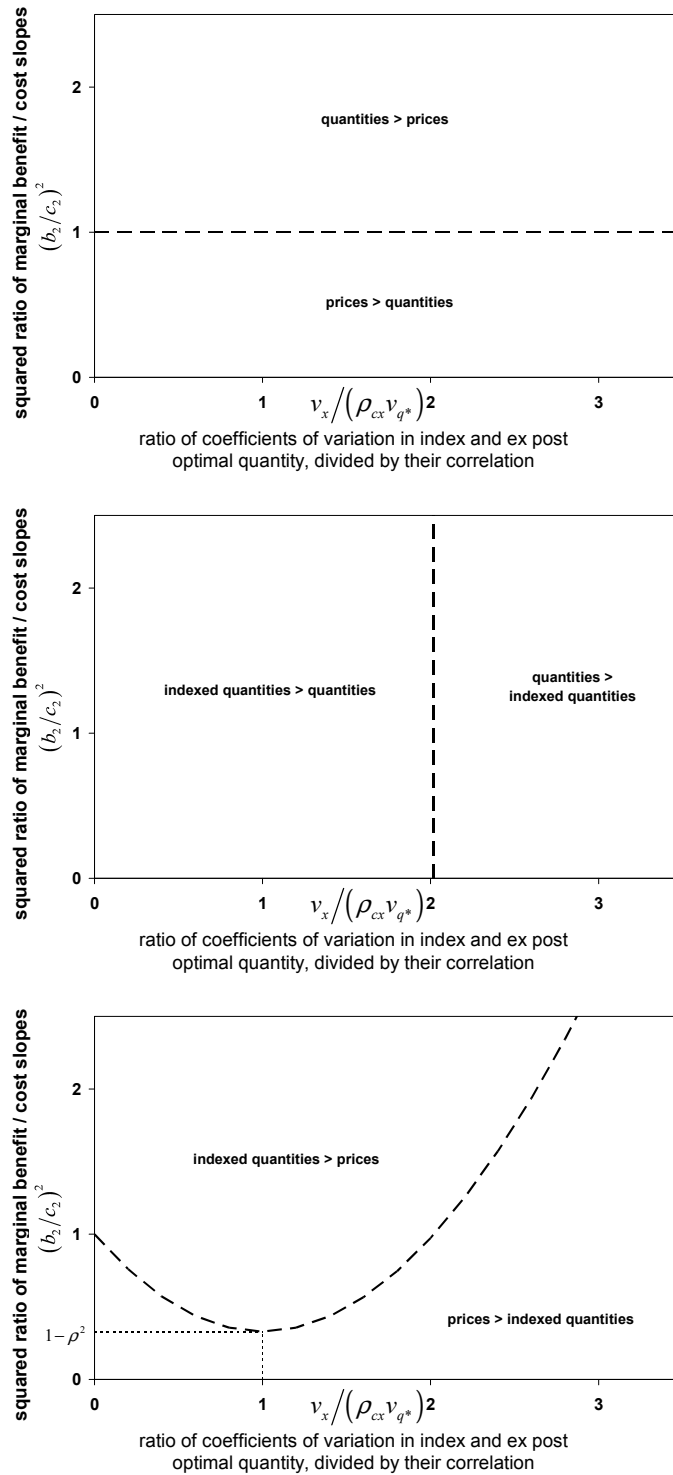


Figure 4. Regions of Relative Advantage for Indexed Quantities, Prices, and Quantities

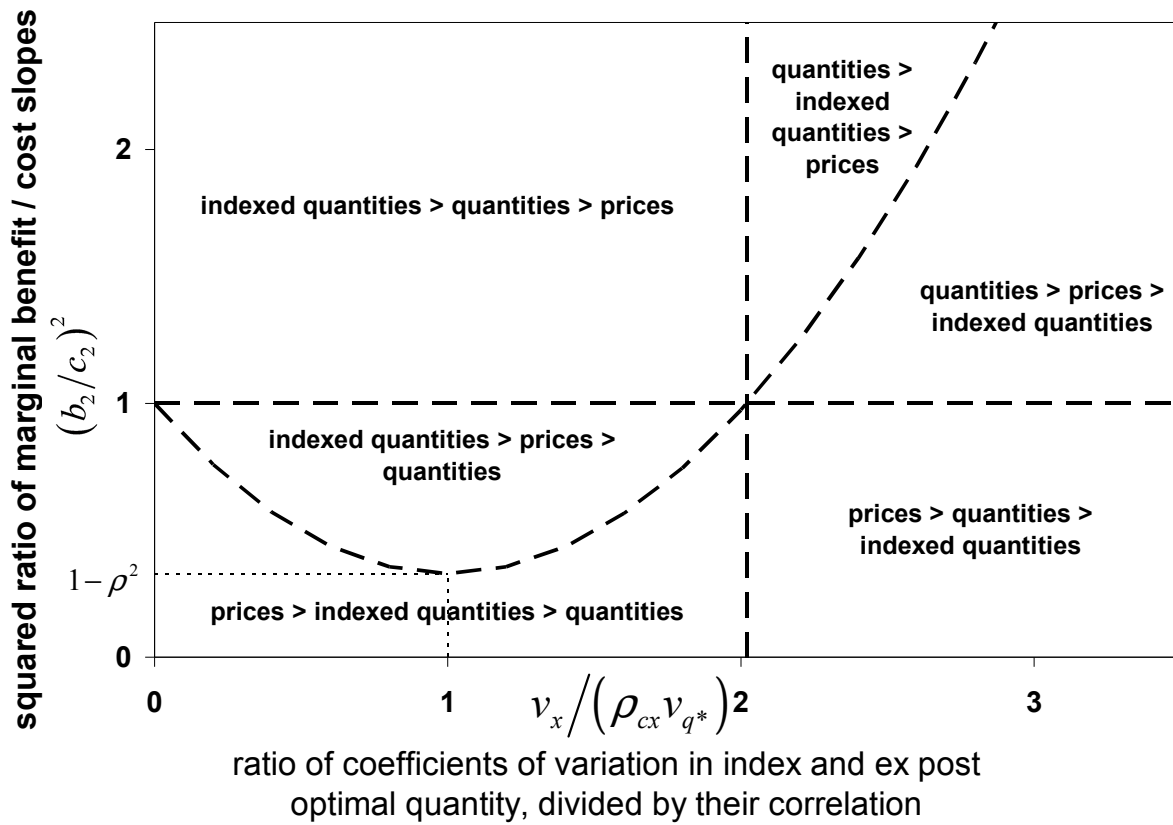


Figure 5. Regions of Relative Advantage for Indexed Quantities, Prices, and Quantities

Table 1. Common Parameters in Relative Advantage Expressions

| Parameter | Symbol | Value |
|---|---------------|---|
| Marginal benefit slope | b_2 | 9.2×10^{-13} \$/ton ² |
| Marginal cost slope (expressed in terms of % reductions) | — | 1.2 \$/(ton \times %) |
| Cost shock standard error from models | σ_m | 1.1 \$/ton |
| Optimal rate of quantity reduction | q^*/\bar{q} | 0.979 |

**Table 2. CO₂ emissions, output, and emissions intensity (2002)
(and implied marginal cost slope)**

| Country | Emissions (\bar{q}) (billion tons CO ₂) | Output (\bar{x}) (trillion \$ GDP) | Intensity (\bar{q}/\bar{x}) (tons per \$1000 GDP) | Marginal cost slope (c_2) (\$/ton ²) |
|------------------|--|---|--|--|
| Australia | 0.41 | 0.55 | 0.88 | 2.8×10^{-7} |
| Brazil | 0.35 | 0.95 | 0.43 | 3.4×10^{-7} |
| Canada | 0.59 | 0.88 | 0.79 | 2.0×10^{-7} |
| China | 3.32 | 1.42 | 2.75 | 3.5×10^{-8} |
| France | 0.41 | 2.18 | 0.22 | 2.8×10^{-7} |
| India | 1.03 | 0.63 | 1.92 | 1.1×10^{-7} |
| Indonesia | 0.30 | 0.26 | 1.37 | 3.9×10^{-7} |
| Iran | 0.36 | 0.17 | 2.52 | 3.2×10^{-7} |
| Italy | 0.45 | 1.47 | 0.36 | 2.6×10^{-7} |
| Japan | 1.18 | 6.60 | 0.21 | 9.8×10^{-8} |
| Korea (South) | 0.45 | 0.80 | 0.66 | 2.6×10^{-7} |
| Mexico | 0.36 | 0.44 | 0.97 | 3.2×10^{-7} |
| Netherlands | 0.26 | 0.59 | 0.51 | 4.5×10^{-7} |
| Poland | 0.27 | 0.20 | 1.60 | 4.3×10^{-7} |
| Saudi Arabia | 0.33 | 0.17 | 2.26 | 3.5×10^{-7} |
| South Africa | 0.38 | 0.21 | 2.07 | 3.1×10^{-7} |
| Spain | 0.34 | 0.87 | 0.46 | 3.4×10^{-7} |
| United Kingdom | 0.55 | 1.58 | 0.41 | 2.1×10^{-7} |
| United States | 5.75 | 10.90 | 0.62 | 2.0×10^{-8} |
| U.S. Electricity | 2.25 | 3.70 | 0.61 | 5.2×10^{-8} |
| World | 24.53 | 41.46 | 0.59 | 4.7×10^{-9} |

Note: U.S. electricity output and intensity measured in terms of trillions of kilowatt-hours.

Table 3. Other Data for Application to Climate Change Policy

| Country | Coef. of variation in emissions ($v_{\bar{q}}$) [†] | Coef. of varitation in output (v_x) | Correlation of emissions and output (ρ_{qx}) [‡] | Standard error of cost shock (σ_c) (\$/ton CO ₂) | $\frac{v_x}{\rho_{cx}v_{q^*}}$ |
|------------------|---|--|---|--|--------------------------------|
| Australia | 0.026 | 0.016 | 0.20 | 3.1 | 3.1 |
| Brazil | 0.046 | 0.032 | 0.72 | 5.1 | 1.0 |
| Canada | 0.035 | 0.023 | 0.54 | 3.9 | 1.2 |
| China | 0.030 | 0.030 | 0.74 | 3.5 | 1.4 |
| France | 0.046 | 0.018 | 0.10 | 5.1 | 3.9 |
| India | 0.040 | 0.021 | 0.20 | 4.5 | 2.6 |
| Indonesia | 0.042 | 0.047 | 0.45 | 4.7 | 2.5 |
| Iran | 0.052 | 0.066 | 0.51 | 5.8 | 2.5 |
| Italy | 0.035 | 0.014 | 0.31 | 4.0 | 1.3 |
| Japan | 0.037 | 0.028 | 0.19 | 4.2 | 4.0 |
| Korea (South) | 0.062 | 0.036 | 0.65 | 6.8 | 0.9 |
| Mexico | 0.048 | 0.034 | 0.53 | 5.4 | 1.3 |
| Netherlands | 0.047 | 0.021 | 0.35 | 5.3 | 1.3 |
| Poland | 0.072 | 0.068 | 0.40 | 8.0 | 2.4 |
| Saudi Arabia | 0.045 | 0.045 | 0.42 | 5.0 | 2.4 |
| South Africa | 0.040 | 0.022 | 0.19 | 4.5 | 3.0 |
| Spain | 0.054 | 0.019 | 0.28 | 6.0 | 1.3 |
| United Kingdom | 0.028 | 0.018 | 0.25 | 3.3 | 2.7 |
| United States | 0.024 | 0.018 | 0.70 | 2.9 | 1.1 |
| U.S. Electricity | 0.025 | 0.020 | 0.84 | 2.9 | 0.9 |
| World | 0.014 | 0.011 | 0.55 | 1.9 | 1.4 |

[†]Approximately equal to v_{q^*} , the coefficient of variation in the ex post optimal quantity level. See equation (25) with $b_2 \approx 0$, $\bar{q}/q^* \approx 1$, and σ_m relatively small.

[‡]Approximately equal to ρ_{cx} , the correlation coefficient between the index and the ex post optimal quantity level. See equation (24) with σ_m relatively small.

Table 4. Relative Advantage of Alternative Climate Change Policies (\$millions)

| Country | Δ_{P-Q} | Δ_{IQ-Q} | Δ_{GIQ-Q} | Δ_{IQ-P} | Δ_{GIQ-P} |
|------------------|----------------|-----------------|------------------|-----------------|------------------|
| Australia | 19 | -2 | 1 | -21 | -18 |
| Brazil | 44 | 22 | 22 | -22 | -22 |
| Canada | 45 | 12 | 12 | -33 | -33 |
| China | 195 | 85 | 96 | -110 | -99 |
| France | 51 | -4 | 1 | -55 | -51 |
| India | 102 | -5 | 4 | -107 | -98 |
| Indonesia | 33 | -7 | 6 | -39 | -26 |
| Iran | 59 | -15 | 15 | -74 | -44 |
| Italy | 35 | 3 | 3 | -32 | -32 |
| Japan | 102 | -25 | 3 | -128 | -99 |
| Korea (South) | 102 | 42 | 42 | -60 | -60 |
| Mexico | 51 | 12 | 14 | -39 | -38 |
| Netherlands | 35 | 4 | 4 | -31 | -31 |
| Poland | 83 | -9 | 13 | -92 | -70 |
| Saudi Arabia | 40 | -5 | 7 | -45 | -33 |
| South Africa | 37 | -3 | 1 | -40 | -35 |
| Spain | 60 | 4 | 4 | -56 | -56 |
| United Kingdom | 29 | -2 | 2 | -31 | -27 |
| United States | 230 | 97 | 97 | -133 | -133 |
| U.S. Electricity | 91 | 55 | 56 | -35 | -35 |
| World | 431 | 77 | 90 | -354 | -341 |

References

- Aase, Knut K. 2004. A pricing model for quantity contracts. *Journal of Risk and Insurance* 71 (4):617-642.
- Carlson, Curtis, Dallas Burtraw, Maureen Cropper, and Karen L. Palmer. 2000. SO₂ Control by Electric Utilities: What are the Gains from Trade. *Journal of Political Economy* 108 (6):1292-1326.
- Ellerman, A. Denny, and Ian Sue Wing. 2003. Absolute versus Intensity-Based Emission Caps. *Climate Policy* 3 (Supplement 2):S7-S20.
- Energy Information Administration. 2004. *International Energy Annual 2002*. Washington, DC.: EIA.
- Fischer, Carolyn. 2003. Combining rate-based and cap-and-trade emissions policies. *Climate Policy* (3S2):S89-S109.
- Helfand, Gloria E. 1991. Standards versus Standards: The Effects of Different Pollution Restrictions. *American Economic Review* 81 (3):622-634.
- Jotzo, Frank, and John C.V. Pezzey. 2005. *Optimal intensity targets for emissions trading under uncertainty*. Canberra: Australian National University.
- Kerr, Suzi, and Richard G. Newell. 2003. Policy-Induced Technology Adoption: Evidence from the U.S. Lead Phasedown. *Journal of Industrial Economics* 51 (3):317-343.
- Li, Chung-Lun, and Panos Kouvelis. 1999. Flexible and risk-sharing supply contracts under price uncertainty. *Management Science* 45 (10):1378-1398.
- Neumann, Anne, and Christian von Hirschhausen. 2004. Less long-term gas to Europe? A quantitative analysis of European long-term gas supply contracts. *Zeitschrift für Energiewirtschaft* 28 (3):175-182.
- Newell, Richard, and William Pizer. 2003. Regulating Stock Externalities Under Uncertainty. *Journal of Environmental Economics and Management* 45:416-432.

- Nichols, Albert L. 1997. Lead in Gasoline. In *Economic Analyses at EPA: Assessing Regulatory Impact*, edited by R. D. Morgenstern. Washington, DC: Resources for the Future.
- Nordhaus, William D. 1994. *Managing the Global Commons*. Cambridge: MIT Press.
- Pizer, William A. 2002. Combining price and quantity controls to mitigate global climate change. *Journal of Public Economics* 85 (3):409-434.
- . 2005. The case for intensity targets. *Climate Policy* 5 (4):455-462.
- Quirion, Philippe. 2005. Does uncertainty justify intensity emission caps. *Resource and Energy Economics* 27:343-353.
- Roberts, Marc J., and Michael Spence. 1976. Effluent Charges and Licenses Under Uncertainty. *Journal of Public Economics* 5 (3-4):193-208.
- Russell, Clifford S., Winston Harrington, and William J. Vaughan. 1986. *Enforcing Pollution Control Laws*. Washington, DC: Resources for the Future.
- Stavins, Robert. 1998. What Can We Learn from the Grand Policy Experiment? Positive and Normative Lessons from SO₂ Allowance Trading. *Journal of Economic Perspectives* 12 (3):69-88.
- Stavins, Robert N. 1996. Correlated Uncertainty and Policy Instrument Choice. *Journal of Environmental Economics and Management* 30 (2):218-232.
- Sue Wing, Ian, A. Denny Ellerman, and Jaemin Song. 2005. *Absolute vs. Intensity Limits for CO₂ Emission Control: Performance under Uncertainty*. Cambridge: MIT.
- Svensson, Lars E. O. 2003. What is wrong with Taylor rules? Using judgement in monetary policy through targeting rules. *Journal of Economic Literature* XLI:426-477.
- Union of Concerned Scientists. 2005. *Renewable Electricity Standards at Work in the States*. Washington: Union of Concerned Scientists.
- Weitzman, Martin L. 1974. Prices vs. Quantities. *Review of Economic Studies* 41 (4):477-491.
- . 1978. Optimal Rewards for Economic Regulation. *American Economic Review* 68 (4):683-691.

Weyant, John P., and Jennifer Hill. 1999. The Costs of the Kyoto Protocol: A Multi-Model Evaluation, Introduction and Overview. *Energy Journal Special Issue*.

Yohe, Gary W. 1978. Towards a General Comparison of Price Controls and Quantity Controls under Uncertainty. *The Review of Economic Studies* 45 (2):229-38.