MIT Joint Program on the Science and Policy of Global Change

Absolute vs. Intensity Limits for CO_2 Emission Control: *Performance Under Uncertainty*

Ian Sue Wing, A. Denny Ellerman and Jaemin Song

Report No. 130
January 2006

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Absolute vs. Intensity Limits for CO_2 Emission Control:
Performance Under Uncertainty

Ian Sue Wing[†], A. Denny Ellerman[*] and Jaemin Song[*]

Abstract

We elucidate the differences between absolute and intensity-based limits of CO_2 emission when there is uncertainty about the future. We demonstrate that the two limits are identical under certainty, and rigorously establish their relative attractiveness under two criteria: preservation of expectations—the minimization of the difference between the actual level and the initial expectation of abatement associated with a one-shot emission target, and temporal stability—the minimization of the variance of abatement due to fluctuations in emissions and GDP over time. Empirical tests of these theoretical propositions indicate that intensity caps are preferable for a broad range of emission reduction commitments. This finding is robust for developing countries, but is more equivocal for developed economies.

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"Prediction is very hard... particularly of the future..." — Niels Bohr

1. INTRODUCTION

This paper addresses an environmental policy question which is simple and fundamental: if a country makes a commitment now to constrain emissions at or below a target level in some future time-period, how can such a target be specified so as to preserve policy makers' expectations about its future economic and environmental impacts? Nowhere is this question more relevant than the design of policies to mitigate the emissions of greenhouse gases (GHGs), especially in international agreements where the preservation of expected outcomes may be an important factor in determining compliance.

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Carbon dioxide (CO_2), the chief GHG, is produced by fossil fuel burning which provides the bulk of energy for economic activity. The absence of inexpensive low-carbon substitutes for fossil energy has led to widespread concern that attempts to cut GHG emissions will cause drastic energy price increases and reductions in output and economic welfare. The GHG emission limits negotiated under the Kyoto Protocol have been criticized as contributing to this unfavorable outcome because these targets are expressed as fixed caps on countries' ability to emit. The absolute character of these caps, it has been argued, fails to account for the possibility that economies and their emissions might grow more quickly than was expected at the time the targets were negotiated, and would therefore inflict larger-than-anticipated economic losses on the Kyoto signatories.

In response to these concerns, a "safety valve" policy has been discussed which would set an upper bound on the marginal costs of abatement (Kopp *et al.*, 2000; Jacoby and Ellerman, 2002), "relative" or intensity-based targets have been adopted in the U.K. Emissions Trading Scheme (U.K. DEFRA, 2001), and the Bush administration in its first term proposed a target to reduce the GHG emission intensity of the U.S. economy by 18% over the coming decade. Yet, while limits on the pollution intensity of output are by far the more common method of constraining emissions in the field of environmental regulation,[1] in the domain of GHG emissions control, intensity limits remain a rarity, with the best-known example being the Bush climate plan.

Implicit in the adoption of all these measures is the recognition of the general principle that the pollution from a source can be limited by specifying an absolute cap on the quantity of emissions that it generates, or by setting a maximum allowable intensity of emissions relative to some measure of either its output or the inputs that it uses in production or consumption. Examples are the units of output or the amount of energy input required by some production process at the firm level, and the volume or value of commodities purchased by consumers at the level of an economic sector, or even GDP at the national level. Such an intensity limit can be imposed either directly, as an emission rate limit or an efficiency standard, or indirectly, by means of technology mandates that have the same effect.

In this paper we elucidate the differences between absolute and intensity limits. We build on the conceptual and theoretical foundation established by Ellerman and Sue Wing to include consideration of the performance of these instruments under uncertainty. In doing so we make three contributions. First, we demonstrate that fixed and flexible limits on emissions are identical

[1] However, absolute emission caps can also be found in a number of programs, for example the SO_2 trading (acid rain), RECLAIM, and the Northeastern NO_x Budget programs in the U.S. Familiar examples of intensity limits are the emission rate limits imposed on nearly all sources under State Implementation Plans in the US, best available control technology mandates, such as in the U.S. New Source Performance Standards or the EU Large Combustion Plant Directive, and the Corporate Average Fuel Economy standards in the US and similar programs in Europe. Although many of the latter do not explicitly specify an emission rate, the effect of these programs is to reduce emission (or energy) intensity and to allow emissions to vary with the level of output. The UK Emissions Trading Scheme is unique in having two sectors, an absolute sector containing firms with absolute limits on GHG emissions and a relative sector containing firms with intensity limits, and allowing trading (with some restrictions) between the two sectors. Rosenzweig and Varilek (2003) review experience with these and other rate-based emission regulations.

when there is no uncertainty about the future. On its face, this may appear to be a trivial point, but there seems to be much misdirection in policy circles on this issue, and we are hard-pressed to find analyses that rigorously establish this basic fact.

Second, we introduce two criteria for judging the relative attractiveness of absolute and intensity-based caps under uncertainty, namely, the degree to which each instrument preserves initial expectations about the level of abatement and cost associated with the emission target, and the degree to which each instrument minimizes the volatility of abatement and cost over time, due to random fluctuations in emissions and GDP.[2]

Third, we test these theoretical propositions using time series data on nations' actual CO_2 emissions and GDP, as well as historical forecasts of these variables. We do this by conducting a backcasting analysis that considers an alternate state of the world in which countries decided to limit their emissions of CO_2 in earlier decades, which allows us to investigate what would have been the optimal choice for the form of their emission cap. Our results indicate that intensity caps may be preferable to absolute caps for a broad range of emission reduction commitments. This finding is robust for less-developed countries, but is more equivocal for developed economies.

The plan of paper is as follows. Section 2 begins with a discussion of the merits of intensity-based emissions limits under uncertainty. In Section 3 we build on the arguments in Ellerman and Sue Wing (2003) to demonstrate that emission limits based on the emission intensity of GDP are equivalent with intensity limits in a world in which there is no certainty. We derive the main theoretical results of the paper in Section 4, where we establish the conditions for the relative attractiveness of fixed versus flexible instruments according to two criteria outlined above. In Section 5 we present and discuss the results of our backcasting analysis. Section 6 concludes with a summary of the implications for climate policy and emission trading.

2. MOTIVATION AND LITERATURE REVIEW

A recent and diverse literature has developed concerning the use of intensity-based and indexed caps in the context of climate policy. The nearly uniform motivation is the widespread perception that less-developed countries (LDCs) would not accept absolute caps because of the perceived limit on economic growth. The proposal by Argentina in November 1999 at the 5th Conference of the Parties to the Kyoto Protocol first drew official attention to this subject (Argentina, 1999; Barros and Conte Grand, 2002). Shortly thereafter, one of President Clinton's economic advisors proposed indexing GHG emission targets to GDP growth as a means of making Kyoto-type caps more acceptable to LDCs (Frankel, 1999). Most recently, the Bush administration's announcement of a target to reduce U.S. GHG intensity by 18% by 2012 (White House, 2002), and its advocacy of intensity limits for developing countries spurred a spate of analyses concerned both with the adequacy of the U.S. target and the more general merits of intensity-based caps.

[2] These are by no means the only criteria that may be used to compare absolute and intensity-based caps. Rosenzweig and Varilek (2003) compare these instruments in terms of their environmental, economic and equity effects.

While analysts appear united in finding that the target set by the Bush administration is indistinguishable from business-as-usual (BAU) emissions, there is a divergence of opinion on the merit of intensity limits more generally. Gielen *et al.* (2002) and Fischer (2003) draw on an old literature in environmental economics, going back to Spulber (1985) and Helfand (1991), which criticizes intensity limits because of the incentive they give producers to use larger quantities of the input or output in which the intensity index is denominated. Compared to absolute limits, intensity caps are a "subsidy" to firms' use of the denominated input or to their production of the denominated output, thereby giving rise to an inefficient allocation of resources. Dudek and Golub (2003) and Müller and Müller-Furstenberg (2003) use different reasoning to arrive at a similar conclusion. They characterize a body of thought that concludes that intensity-based caps offer no clear advantage over absolute caps because of the greater uncertainty of the environmental outcome and problems of implementation.

Conversely, Kim and Baumert (2002), Strachan (forthcoming) and Kolstad (2005) all find merit in the concept of intensity-based caps because of the reduction in uncertainty in the economic outcome gained by indexing the cap to GDP and, crucially, the effect on the countries' willingness to participate in international agreements. Along these lines, Jotzo and Pezzey (2004) provide a theoretical analysis and simulations of binding absolute and intensity caps (as well as non-binding targets) in which parties are assumed to posses varying degrees of risk aversion to unexpectedly high-cost outcomes with particular attention given to LDC participation. They find that intensity-based caps are superior to absolute caps for circumstances where all parties to a treaty place some positive value on global abatement, face positive abatement costs, and are risk-averse in varying degrees to high cost outcomes. For individually-varying but positive valuations on global abatement, parties would be willing to embrace tighter binding targets in return for the removal of some of the uncertainty relating to high cost outcomes.

Our own contribution to this debate (Ellerman and Sue Wing, 2003) has focused squarely on the nature of the relevant uncertainties, while treating absolute and intensity limits with equanimity. Under conditions of certainty, equivalent absolute and intensity-based caps would have identical effects, and that the outcomes between the two forms differ only to the extent that realized values for GDP and other relevant variables diverge from expectation. The present paper seeks to further clarify this point.

We are motivated by the fact that, in spite of both the foregoing analyses and the significant experience that industrialized nations already have with intensity limits in the context of domestic environmental regulation, there is still a lack of familiarity with the use of intensity limits for CO_2 abatement at the international level. The pervasiveness of this problem is evident from comparisons between Kyoto's absolute emission targets and intensity limits, which characterize the latter as economically advantageous while being environmentally disadvantageous.

Negative reactions to the Bush climate change plan uniformly argue that indexing future emission constraints to GDP would allow GHG emissions to continue to rise when GDP is increasing, as it is generally expected to do.[3] But such criticisms belie confusion of the

[3] See *e.g.*, "Blowing Smoke", *The Economist*, Feb. 14, 2002, p. 27.

stringency of the Bush target with the *form* of the instrument employed in its execution.[4] In spite of the fact that these are two separate issues, the unstated implication appears to be that intensity limits allow emissions to continue growing unabated, as if restricting emissions to grow more slowly than they would in a BAU scenario constitutes an absence of real reductions.

The flaw in this argument is that it ignores the counterfactual no-policy path of emissions, whose unfettered growth may well exceed the limit mandated by the intensity cap, and which may, as in the case of Russia, be lower than an absolute cap. For this reason, the presumption that intensity-based limits are inherently less stringent is wrong, as Ellerman and Sue Wing (2003) explain. A nation's decision to set an absolute cap on emissions is invariably informed by a sense of the limit's expected effects, which typically incorporate a forecast of GDP in the future period when that instrument is slated to enter into force. Given this set of expectations, there are numerous schemes for specifying GDP-indexed emission targets that are entirely equivalent to the absolute limit, a point which demonstrate in Section 3.

The essential caveat to this equivalence is uncertainty about the future. Of principal concern is the ex-post level of the emission limit that results from imposing either instrument ex ante. Different instruments whose effects are predicted to be equivalent based on ex ante expectations of GDP may turn out not to hold if actual GDP in the target period diverges from its expected level. In particular, the level of an intensity-based cap will fluctuate in proportion to the ratio of actual to expected GDP.

This phenomenon is the basis of the more nuanced critique of intensity limits articulated by Dudek and Golub (2003). The argument is that, relative to an absolute ceiling on emissions that is fixed ex ante, an intensity cap creates the potential for an environmentally adverse outcome if GDP is higher than expected. In this case the cap adjusts upward, making the target less stringent in absolute terms. This also appears to be the motivation behind the studies by Fischer (2003) and Geilen *et al.* (2002), namely that output subsidy effect gives countries an incentive to "grow their way out of" a GDP-indexed emission target, rather than undertake costly emission reductions.

We argue that both of these concerns are unfounded. The output subsidy critique of indexed caps applies only in so far as the limit is faced by individual producers. It does not apply at the country level because the indexation variable, aggregate output, does not figure in firm-level decisions. Within a nation, producers could be expected to take into account the fact that the emissions cap would be adjusted upward (or downward) but the practical incentive they would face is a lower (or higher) cost for the use of allowances than would otherwise be the case. Individual firms would not face any greater or lesser constraint as a result of variations in the

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[4] This is perhaps because the stated intent of Bush target is to take future economic growth into account: "This new approach focuses on reducing the growth of GHG emissions, *while sustaining the economic growth* needed to finance investment in new, clean energy technologies." (White House, 2002) [our emphasis]. Its stringency (or lack thereof) is a legitimate concern. The target calls for an 18% reduction in the GHG emission intensity of the U.S. economy by 2012, where the DOE/EIA (2004) forecast projects a decline in the CO_2-GDP ratio of 15% by 2010. By contrast, the reduction in the CO_2 emission intensity over the same period implied by the U.S. Kyoto target is greater than 40%. Moreover, the Bush target is specified not as a legally-binding limit, but as a goal to be achieved through an array of voluntary actions, creating the potential for little or no abatement to take place.

output of, or the inputs to, their production processes. Moreover, it seems implausible that countries would seek faster economic growth not for its own sake, but as a means of evading abatement costs.

By contrast, there has been little discussion of the merits of intensity-based emission caps when GDP growth is *less* vigorous than expected. Ellerman and Sue Wing (2003) show that in this case the level of the cap will adjust downward, making the target *more* stringent in absolute terms. They argue intuitively that an intensity limit trades off less stringent control of emissions in a state of the world with higher than expected economic growth for more stringent control in a state of the world with lower than expected growth. Mirroring this ex post divergence in stringency will be ex post divergence in the quantity and cost of abatement. For any level of counterfactual emissions the quantity and cost of abatement that result from an intensity limit will be lower in a high-growth state of the world and higher in a low-growth state than occasioned by an absolute limit.

Our aim in this paper is to elucidate the implications of uncertainty in baseline emissions and GDP for policy makers' choice between an absolute and an intensity cap. In particular, in Section 4 we rigorously establish the conditions under which one or the other form of emission limit will give rise to greater variance in cost outcomes, and in Section 5 we test which form of the limit would have produced less variance in abatement cost, using historical data for a number of countries and time periods. All of the analyses focusing on the merits of reducing uncertainty assume that emissions and GDP are positively correlated. Like Jotzo and Pezzey (2004), we find that the positive correlation between emissions and GDP is often large enough that intensity caps reduce the variance of cost outcomes. However, we also demonstrate that this result has failed to hold for many high-emitting countries over varying periods of time.

Given that policy makers will tend to set the level of an emission target based on their expectations of the economic and environmental conditions that prevail when that target enters into force, it is critical to understand how the two instruments may differ in their ability to generate outcomes under uncertainty that are consistent with the initial expectations that led the setting of the target in the first place.

When emissions and GDP are positively correlated, counterfactual emissions will tend to increase with economic growth, and the quantity and cost of abatement warranted by an absolute cap ex post will tend to exceed (fall short of) some initial expectation if GDP grows more (less) rapidly than initially forecast. By contrast, an intensity cap will adjust the required level of abatement and the associated cost in a manner that will tend to preserve the initial expectation, though the extent of this benefit is an empirical matter.

It is therefore crucial to understand how the levels of abatement and the costs of emission control differ under the two instruments, because the variability of these expectations will influence the cost of emission reduction programs through its effect on incentives for sources to invest in process changes or pollution control equipment, undertake early abatement actions in advance of the cap binding, purchase emission rights when the emission constraint binds, or bank emission permits over time.

At the heart of our concern are the phenomena of adjustment costs and irreversibility in investment. Time-to-build lags in the installation of new capital for reducing emissions implies that attempts to invest in rapidly abatement capacity are likely to incur additional "adjustment" costs. Moreover, such investments are irreversible in the sense that abatement capital is "sunk"—once installed, equipment and structures dedicated to reducing emissions cannot be converted into consumption goods or other forms of productive capital without incurring large costs (Fisher, 2001).

The first of these phenomena is relevant in cases where BAU emissions are higher than expected, so that sources face the high costs of quickly installing additional abatement capital to remain in compliance with a fixed cap. The second is important where BAU emissions are lower than expected, with opportunity costs of idle capacity that attend over-investment in abatement capital. The crucial point is that while baseline uncertainty creates the downside risk of adjustment costs on one hand and opportunity costs on the other, policy makers may specify an emission target in intensity terms as a hedge against investing too little or too much in abatement capacity. The effectiveness of doing so depends on the stochastic properties of emissions and GDP.

Furthermore, one can think of these risks as being present at a single instant, or over some policy horizon. The former case can occur where a one-time emission target is specified in advance of the date of its entry into force, as in the case of the first Kyoto commitment period. If investment in abatement capital is based on initial expectations, policy makers' incentive is to select the form of the limit which minimizes the difference between actual and initially-expected abatement. We call this principle the "expectations preservation criterion".

The latter case occurs where emissions are restricted to some target trajectory over a budget horizon. Here, uncertainty can thought of as the stochastic fluctuations in the level or the growth rate of BAU emissions, which give rise to periods of over- and under-capacity in abatement. Therefore, to minimize unanticipated costs, policy makers have an incentive to choose the form of the emission limit which minimizes the volatility in the trajectory of abatement. We call this principle the "temporal stability criterion".

3. FLEXIBLE, GROWTH- AND INTENSITY-BASED EMISSION LIMITS: EQUIVALENCE UNDER CERTAINTY

Our first task is to establish the equivalence of absolute and intensity limits under certainty. Our analytical approach, which builds on Ellerman and Sue Wing (2003), considers a nation which must commit to a future cap on its emissions, and wishes to choose the instrument that best achieves this objective. Time, which we denote by the index t, lasts from an initial period zero in which the commitment to abate is made, to a final period T , in which the emission limit chosen at $t = 0$ enters into force. Let Q_t denote emissions and Y_t denote GDP in period $t \in [0, T)$. In the initial period emissions and GDP are known with certainty, and therefore so is the emission intensity, γ, of the economy:

$$\gamma_0 = Q_0 / Y_0 . \qquad (1)$$

Suppose that at time zero the country chooses to limit its emissions in future period T to a level $\underline{Q}_T$, conditional on expectations of the growth the economy and baseline emissions.

The expectations that lead to this course of action are as follows. Letting E_t be an operator that denotes expectations at time t, the expectation in period zero of baseline emissions in T is $E_0[Q_T]$, which implies that the period-zero expectation of abatement at T is:

$$E_0\left[A_T^A\right] = E_0\left[Q_T\right] - \underline{Q}_T \,. \tag{2}$$

This absolute cap on emissions can be transformed into an emission intensity target according to the period-zero forecast of GDP at time T: $E_0[Y_T]$. If the cap is expected to be binding at T, the initial expectation of the emission intensity of output in that future period is:

$$E_0\left[\underline{\gamma}_T\right] = \underline{Q}_T \big/ E_0\left[Y_T\right], \tag{3}$$

implying that the initially-expected abatement with this instrument is the same as in eq. (1), *i.e.*:

$$E_0\left[A_T^I\right] = E_0\left[Q_T\right] - E_0\left[\underline{\gamma}_T\right] E_0\left[Y_T\right]. \tag{4}$$

The nation in question would only commit to such a limit if it was perceived that the cost of making the necessary abatement from BAU level were within some acceptable range. Thus, given an abatement cost schedule $C(A)$ which we assume is positive, monotonic increasing and known with certainty, the expectation at time zero that the cost of reducing emissions at T under either instrument is $C\left(E_0\left[A_T^A\right]\right) = C\left(E_0\left[A_T^I\right]\right)$.

As we step forward in time closer to T, forecasts—and thus expectations—are likely to change as uncertainty about the economic and environmental conditions under which abatement will actually take place is reduced. Similar to eqs. (2) and (4), expectation at t about abatement at T under the absolute cap is:

$$E_t\left[A_T^A\right] = E_t\left[Q_T\right] - \underline{Q}_T \tag{5}$$

and under the intensity cap is:

$$E_t\left[A_T^I\right] = E_t\left[Q_T\right] - E_t\left[\underline{\gamma}_T\right] E_t\left[Y_T\right]. \tag{6}$$

In general, eqs. (5) and (6) will diverge. The difference in the expected level of abatement is:

$$E_t\left[A_T^A\right] - E_t\left[A_T^I\right] = E_t\left[\underline{\gamma}_T\right] E_t\left[Y_T\right] - \underline{Q}_T \,. \tag{7}$$

However, in a world of certainty the expected and actual quantities of emissions and levels of GDP are identical, so that $E_0[Q_T] = E_t[Q_T] = Q_T$ and $E_0[Y_T] = E_t[Y_T] = Y_T$. The form of the emission limit is therefore irrelevant.

3.1 Emission Targets Based on the Level of Emission Intensity

Imagine that the form of the emission limit agreed to at time zero is a combines an absolute limit, $\underline{Q}_T$, with the intensity target specified by the product of expected intensity defined by eq. (3) and actual GDP at time T. This GDP-indexed limit, introduced by Ellerman and Sue

Wing (2003), specifies the actual cap on emissions, $\tilde{Q}_T$, as the convex combination of a fixed cap and an intensity target:

$$\tilde{Q}_T = (1-\eta)\underline{Q}_T + \eta E_0[\underline{\gamma}_T]Y_T . \qquad (8)$$

Here, $\eta \in [0,1]$ is a sensitivity parameter whose value is selected to represent the degree to which the limit accommodates changes in GDP from its forecast level: when η = 0 the limit is absolute, and when η = 1 the limit adjusts fully to the change in GDP. Obviously, if $E_0[Y_T] = Y_T$ then $\tilde{Q}_T = \underline{Q}_T$, implying that the absolute and the intensity limit are identical under certainty.

3.2 An Emission Target Based on the Growth of GDP

Now consider a limit specified in terms of the rate of growth of emissions, that limits them to some maximum allowable fraction, $\bar{\theta}$, of the expected growth of GDP:

$$(\underline{Q}_T / Q_0 - 1) = \bar{\theta}(E_0[Y_T]/Y_0 - 1) . \qquad (9)$$

For the adjustable limit specified above to behave similarly to the growth-based target, it must be the case that:

$$(\tilde{Q}_T / Q_0 - 1) = \tilde{\theta}(E_0[Y_T]/Y_0 - 1) , \qquad (10)$$

in which $\tilde{\theta}$ specifies the fraction of the rate of GDP growth at which emissions are allowed to increase. It was just demonstrated that $\tilde{Q}_T = \underline{Q}_T$ under certainty. Clearly, if this is the case, eqs. (9) and (10) are identical iff $\tilde{\theta} = \bar{\theta}$, implying that emissions are allowed to grow by the same fraction of GDP under both the absolute and the intensity cap, so that both instruments are identical. It is important to realize that under uncertainty this result does not generally hold. Substituting eqs. (8) and (9) in eq. (10), solving for $\tilde{\theta}$ and rearranging yields:

$$\tilde{\theta} = \frac{1}{E_0[g_Y]}\left[\left((1-\eta) + \eta E_0[\underline{\gamma}_T]/\underline{\gamma}_T\right)\left(1 + \bar{\theta}E_0[g_Y]\right) - 1\right], \qquad (11)$$

where $E_0[g_Y] = E_0[Y_T]/Y_0 - 1$ is the period-zero forecast of the rate of GDP growth from zero to T, and $\underline{\gamma}_T = \underline{Q}_T / Y_T$ is the realized emission intensity of GDP at time T. This expression shows that $\tilde{\theta}$ and $\bar{\theta}$ diverge to the extent that actual emissions or GDP at T differ from their forecast values, and that this divergence is mitigated as $\eta \to 0$.

3.3 An Emission Target Based on the Growth of Emission Intensity

Now imagine an emission limit specified in terms of an upper bound on the future rate of decline in the economy's emission intensity. Denoting this rate by $\bar{\phi}$ we have:

$$\bar{\phi} = \frac{\underline{Q}_T / E_0[Y_T]}{\gamma_0} - 1 . \qquad (12)$$

For an intensity limit to behave in the same way as under the intensity-based or growth-based targets, it must be the case that:

$$\tilde{\phi} = \frac{\tilde{Q}_T \,/\, E_0[Y_T]}{\gamma_0} - 1, \qquad (13)$$

where $\tilde{\phi}$ specifies the rate of decline in the emissions intensity of the economy. As before, once $\tilde{Q}_T = \underline{Q}_T$, the limits produce identical effects iff $\tilde{\phi} = \overline{\phi}$, *i.e.*, the economy's emission intensity is mandated to decline at the same rate under both the absolute and the intensity cap, implying the both instruments are identical. It is also the case that the foregoing result does not generalize in the presence of uncertainty. Substituting eqs. (8) and (12) in eq. (13) and solving for $\tilde{\phi}$ yields, after rearrangement:

$$\tilde{\phi} = (1+\overline{\phi})\Big((1-\eta) + \eta Y_T \,/\, E_0[Y_T]\Big) - 1. \qquad (14)$$

Once again, $\overline{\phi}$ and $\tilde{\phi}$ diverge to the extent that actual emissions or GDP at T differ from their forecast values, and this divergence is mitigated as $\eta \to 0$.

In all of the foregoing forms of the limit, the target level of emissions, $\underline{Q}_T$, is achieved. The three methods for setting the target give rise to identical outcomes, and are therefore equivalent.

4. ABSOLUTE AND INTENSITY LIMITS: CHOICE UNDER UNCERTAINTY

We now have the mathematical machinery in place to address the question of how abatement under the intensity target specified in Section 3.1 diverges from that of an absolute target in the presence of uncertainty. We focus on this specification because it is the most analytically tractable of the three, and leave the others to future research. Our goal is to establish the conditions under which one or the other forms of the emission limit minimizes the variance in the level (and therefore, the cost) of abatement. We develop theoretical results for the expectations preservation criterion, and then show that the results for temporal stability criterion are essentially the same.

4.1 The Criterion of Preservation of Expectations

To analyze which instrument generates a level of abatement closer to the initially-expected quantity, we use the mathematical setup of the previous section. Our approach is deliberately simple. From eqs. (5) and (6) we note that the expectation of abatement under the absolute cap depends solely on the expectation of counterfactual emissions, while that under the intensity cap depends on expectations of both counterfactual emissions and GDP. The variance of abatement under the absolute cap is thus:

$$\mathrm{var}\left[A_T^A\right] = \mathrm{var}\left[Q_T\right], \qquad (15)$$

while under the hybrid cap it is:

$$\mathrm{var}\left[A_T^I\right] = \mathrm{var}\left[Q_T\right] + \left(\eta E_0\left[\underline{\gamma}_T\right]\right)^2 \mathrm{var}\left[Y_T\right] - 2\eta E_0\left[\underline{\gamma}_T\right]\mathrm{cov}\left[Q_T, Y_T\right]. \qquad (16)$$

One might well conjecture that the variance in the expected effect of the latter instrument will exceed that of the former.[5] We establish whether the volatility in expectations of abatement is

[5] The actual result of course depends on the sign of the covariance between expectations of Q_T and Y_T, but we shall use this as our reference assumption.

higher under one instrument or the other by subtracting (15) from (16) and rearranging. The variance of expected abatement is larger for the absolute cap iff:

$$\eta E_0\left[\underline{\gamma}_T\right]/\,2 < \operatorname{cov}\left[Q_T, Y_T\right]/\operatorname{var}\left[Y_T\right], \tag{17}$$

implying that an intensity limit will be preferred.

The intuition behind eq. (17) becomes clearer when it is approximated in normalized form:

$$\frac{\eta}{2}\underline{Q}_T \,/\, \bar{Q}_T < \rho^f\left[Q_T, Y_T\right] v^f\left[Q_T\right] / \, v^f\left[Y_T\right]. \tag{18}$$

The subscript f signifies that the right-hand-side variables are calculated using data from a sequence of forecasts of conditions in period T made a time steps 0 to T–1. Thus, $\rho^f[Q_T, Y_T]$ is the correlation across forecasts between emissions and GDP, $v^f[Y_T]$ and $v^f[Q_T]$ are the forecast coefficients of variation of GDP and emissions, $\bar{Q}_T = E_0^f\left[Q_T\right]$ is the forecast baseline emissions level in the initial period in which the limit is adopted, and $\underline{Q}_T \,/\, \bar{Q}_T$ expresses the target as a fraction of the initially expectation of BAU emissions.

Eq. (18) is the main result of the paper. We interpret it by first considering the choice between an absolute and a fully indexed cap (*i.e.*, η = 0 or 1) for a given emission target $\underline{Q}_T$. If emissions and GDP are perfectly correlated and have similar degrees of variability, so that the right-hand side of (18) is unity, then for a policy maker to be indifferent between an absolute and an intensity cap requires $\underline{Q}_T = 2\bar{Q}_T$. This is a contradiction, since for a binding emission target we must always have $\underline{Q}_T < \bar{Q}_T$. This inequality is consistent with eq. (17) above, and implies that an intensity limit will always be preferred.

In reality, the right-hand side of eq. (18), which we indicate by the variable Z^{EP}, is made up of variables which are attributes of the economy, and are not amenable to manipulation by policy makers. Where there is a sufficiently weak positive correlation between emissions and GDP ($0 < \rho^f < 1$) or the volatility of GDP is sufficiently large relative to emissions ($v^f\left[Q_T\right]/\, v^f\left[Y_T\right] < 1$), Z^{EP} may be small enough that:

$$\underline{Q}_T > 2\bar{Q}_T Z^{EP},$$

in which case an absolute cap will be preferred to an intensity limit.[6] However, if we relax the assumption of complete indexation, it is intuitively clear that a partially-indexed cap will *always* be preferred, since it is always possible to choose a sufficiently small value for η to shift the sign of the inequality so that:

$$\underline{Q}_T < \frac{2}{\eta}\bar{Q}_T Z^{EP}. \tag{19}$$

The implication of eq. (18) is that for an absolute limit to better preserve initial expectations about the level of abatement necessary to comply with a cap $\underline{Q}_T$, the fractional reduction in

[6] Mathematically, it is also the case that an absolute cap will always prevail in the implausible situation where GDP and emissions are negatively correlated (*i.e.*, $-1 < \rho^f < 0$).

emissions due to the cap must exceed the product of the correlation between GDP and emissions and the variability of emissions relative to GDP by at least a factor $\omega = \eta / 2$. Given that in most economies both emissions and GDP are increasing, it is reasonable to expect forecasts of Q and Y to be strongly positively correlated. This suggests that in order to preserve initial expectations about the burden of abatement in an economy with steady economic growth—and a consequent tendency for a low value of $v^f\left[Y_T\right]$ relative to $v^f\left[Q_T\right]$—stringent emission targets should be implemented using intensity limits, while lax targets should employ absolute limits.

This tradeoff is illustrated in **Figure 1**, which plots the fraction of initially-expected baseline emissions on the horizontal axis and the value of Z^{EP} on the vertical axis. The horizontal line HH' represents the cutoff value for the initial expectation of intensity given by the right hand side of eq. (18). Above this schedule the variance in forecasts of the intensity cap is larger, while below it the forecast variance of the absolute cap predominates. The diagonal ray OJ gives the locus of values of $\omega \underline{Q}_T / \overline{Q}_T$. Its maximum slope, which corresponds to the ray OJ', is $^1/_2$. The point K where HH' and OJ intersect represents the equality of both sides of eq. (18), and defines the level of an emission target $\underline{Q}_T = \underline{Q}*$ below (above) which an intensity limit will exhibit the lower (higher) variance, and thus will (will not) be the preferred instrument.

The value of $\underline{Q}*$ and the expected counterfactual level of emissions determine the quantity of abatement that a nation should undertake using a particular instrument. To see this, assume that the emission target is given by the vertical line LL'. Then, according to our criterion, the maximum amount of abatement that should be undertaken using an absolute cap is $1 - L$, with a switch to an intensity limit if the target level of emissions $\underline{Q}_T < Q*$. The corollary is that if the target is set at a level less than $Q*$, say at MM', then any amount of abatement should be undertaken using an intensity limit. Therefore, if the OJ schedule intersects with the BAU emissions line above the HH' cutoff then an absolute cap is preferred, whereas if the point of intersection is below HH' then an intensity cap is preferred.

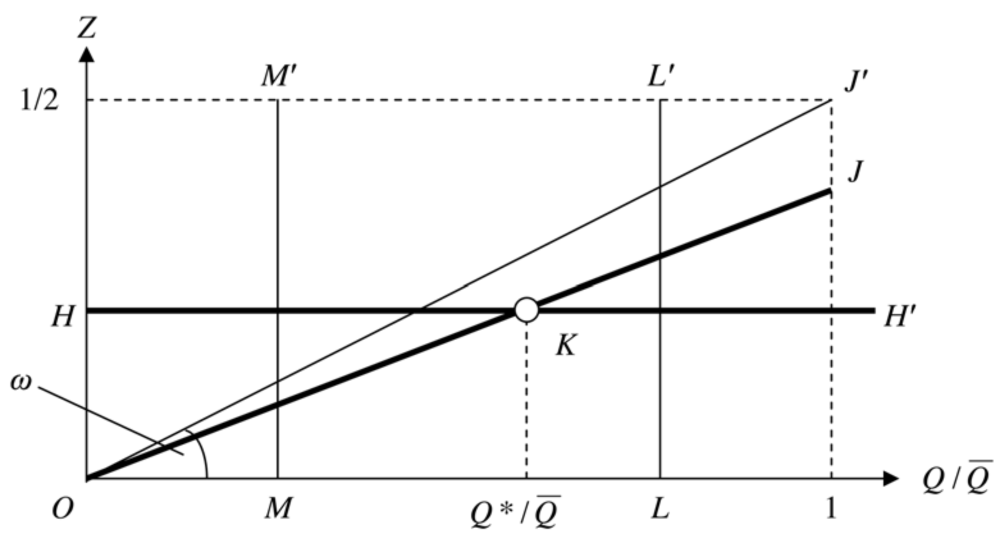

Figure 1. The Tradeoff Between Absolute and Intensity Limits.

Eq. (19) suggests that a hybrid limit gives policy makers greater control by enabling them to choose the degree of GDP indexation of an emission target which provides the optimal hedge against uncertainty in future abatement and cost. The value of the indexation parameter that minimizes the variance in expectations of abatement can be found by differentiating (16) with respect to η and solving the first-order condition to yield:

$$\eta^* = \frac{E_0^f\left[Y_T\right]\mathrm{cov}^f\left[Q_T, Y_T\right]}{\underline{Q}_T\,\mathrm{var}^f\left[Y_T\right]} = \frac{Z^{EP}}{\underline{Q}_T / \bar{Q}_T}\,. \tag{20}$$

Substituting this expression into eq. (16) and simplifying gives the minimized variance of abatement:

$$\mathrm{var}\left[A_T^I\right] = \left(1 - \rho^f\left[Q_T, Y_T\right]^2\right)\mathrm{var}\left[Q_T\right], \tag{21}$$

which is unambiguously less than the variance of abatement under the absolute limit, and is less volatile than an emission cap that is fully indexed to GDP ($\eta = 1$) iff:

$$\underline{Q}_T > \bar{Q}_T Z^{EP}\,. \tag{22}$$

If the condition above is satisfied, then policy makers should choose $0 < \eta^* < 1$, and full indexation otherwise.

This implication of optimal indexation is captured by Figure 1. Setting η according to eq. (20) makes the slope of *OJ* an increasing function of the level of the desired limit on emissions. At the point where the value on the horizontal axis is equal to the fractional emission reduction due to the constraint, $\underline{Q}_T / \bar{Q}_T$, the height of the *OJ* schedule will always be half the vertical distance of the cutoff value given by *HH'*. Therefore, under optimal indexation, setting a more stringent emission target results in the counter-clockwise rotation of *OJ* and a corresponding leftward shift in the indifference point until *OJ* is congruent with *OJ'*, where full indexation is achieved.

4.2 The Criterion of Temporal Stability

We now investigate which instrument results in lower volatility of abatement over time. We consider a commitment period which is *T* time-steps long, indexed by $t \in [0, T]$, in which counterfactual levels emissions and GDP are given by Q_t and Y_t, respectively. For simplicity we focus on the effects of an absolute cap on emissions set a constant level $\underline{Q}$, and an equivalent flexible limit based on the emission intensity of GDP.

In each period, abatement under the absolute cap is:

$$A_t^A = Q_t - \underline{Q}\,. \tag{23}$$

which implies that the variance of abatement over the policy horizon is $\mathrm{var}\left[Q_t\right]$, as in eq. (15). It is generally the case that emissions and GDP do not maintain a fixed relationship as they evolve through time.[7] In a growing economy, a fixed cap on intensity results in an emissions cap

[7] For example, using data on a panel of countries, Stoker *et al*. (1998) find that the CO_2 emission elasticity of GDP first increases, then peaks and finally declines as per capita income rises from the levels in very poor countries to those that prevail in rich nations.

that is progressively less binding over time. Therefore, in order to constrain emissions at a constant level $\underline{Q}$, an emission limit in the form of a warranted maximum emission intensity of GDP must be ratcheted down over time at the rate of GDP growth.

Abatement under the indexed cap is:

$$A_t^I = Q_t - \tilde{Q}_t = Q_t - \left((1-\eta)\underline{Q} + \eta\underline{\gamma}_t Y_t\right), \tag{24}$$

where $\underline{\gamma}_t = \underline{Q} / \overline{Y}_t$ is the ceiling on the emission intensity of the economy due to the cap, and $\overline{Y}_t$ denotes the ex-ante prediction of the evolution of GDP over the policy horizon. The variance of emissions associated with the intensity limit is:

$$\operatorname{var}\left[A_t^I\right] = \operatorname{var}\left[Q_t\right] + \left(\eta\underline{\gamma}_t\right)^2 \operatorname{var}[Y_t] - 2\eta\underline{\gamma}_t \operatorname{cov}[Q_t, Y_t], \tag{25}$$

which implies that the variance of abatement is larger for the absolute cap iff:

$$\frac{\eta}{2}\underline{\gamma}_t < \operatorname{cov}\left[Q_t, Y_t\right] / \operatorname{var}\left[Y_t\right]. \tag{26}$$

We approximate this expression in normalized form as follows:

$$\frac{\eta}{2}\underline{Q} / \overline{Q}_t < \rho^h\left[Q_t, Y_t\right] v^h\left[Q_t\right] / v^h\left[Y_t\right], \tag{27}$$

a result which is almost identical to eq. (18). The superscript *h* signifies that the right-hand-side variables are calculated using historical time series for the periods immediately prior to *t*. Thus, $\rho^h[Q_t, Y_t]$ is the historical correlation between emissions and GDP, and $v^h[Y_t]$ and $v^h[Q_t]$ are the historical coefficients of variation of GDP and emissions. In a departure from the previous specification, $\overline{Q}_t = Q_0 e^{\overline{g}_Q^h t}$ is the projection of baseline emissions in period *t* using the historical average rate of growth of emissions $\overline{g}_Q^h$, and $\underline{Q} / \overline{Q}_t$ expresses the target as a fraction of this projected BAU emission level.

Eqs. (27) and (18) are identical in their implications. We use the variable Z^{TS} to denote the right-hand side of eq. (27). Then, according to the temporal stability criterion, an absolute cap will be preferred to a fully-indexed cap if:

$$\underline{Q} > 2\overline{Q}_t Z^{TS},$$

a situation which arises where emissions grow slowly relative to output, the correlation between the growth rates of emission and GDP is low, or the volatility of GDP growth exceeds that of the growth of emissions. The argument of the previous section that a partially-indexed cap is always preferable applies here as well.

For an absolute limit to result in smaller fluctuations in the path of abatement necessary to comply with an emission target $\underline{Q}$, the fractional reduction in the emission intensity of GDP due to the cap must exceed the product of the ratio of the emissions growth rate and the GDP growth rate, the correlation between the growth rates of GDP and emissions, and the variability of emissions relative to GDP by at least a factor $\omega = \eta / 2$. This suggests that in order to minimize the volatility of abatement over time in an economy with steady economic growth—and a consequent tendency for a low value of $v^h\left[Y_t\right]$ relative to $v^h\left[Q_t\right]$—stringent emission targets should be implemented using intensity limits, while lax targets should employ absolute limits.

This tradeoff is also captured by Figure 1. Here, *HH'* denotes the value of Z^{TS} above which the temporal volatility of the intensity cap is larger and below which the volatility of the absolute cap predominates. As before, the point *K* denotes the level of the emission target $\underline{Q} = Q*$ below (above) which the use of an intensity cap will exhibit lower (higher) variance, and thus will (will not) be preferred. Here, however, the key difference is that emission targets such as those represented by *LL'* and *MM'* will shift to the left over time as emissions increase with the growth of the economy. The fact that any such loci are increasingly likely to be overtaken by $Q*$ predisposes policy makers toward the use of an intensity limit.

This dynamic behavior is especially important where the level of the emission target changes over time. For example, consider the "slow-stop-reverse" emission trajectory outlined by the White House (2002).[8] This emission target is progressively decoupled from the future BAU path of emissions, implying that *LL'* will move leftward at a rate that starts out slower than $\bar{g}_Q^h$ and increases over time.

If such a policy were implemented in a developing country where BAU emissions are growing rapidly, it would be optimal to set an absolute cap initially but then rapidly transition to an intensity limit. Conversely, in a mature economy with comparatively slow BAU emissions growth, the shift in *LL'* might well be insufficient for it to fall below $Q*$ if the initial level of the target is not significantly less than BAU emissions, implying that an absolute cap would be preferred. These examples emphasize that the benefit of intensity limits depends on how both the initial level of the target and the baseline emissions growth rate interact with the emissions-output correlation and the volatility of emissions relative to that of GDP.

Finally, the value of the indexation parameter which provides the optimal hedge against temporal fluctuations in abatement and cost can be specified in a manner analogous to eq. (20):

$$\eta* = \frac{Z^{TS}}{\underline{Q} / Q_t}. \tag{28}$$

The minimized variance of abatement is then the same as eq. (21):

$$\mathrm{var}\left[A_t^I\right] = \left(1 - \rho^h\left[Q_t, Y_t\right]^2\right)\mathrm{var}\left[Q_t\right], \tag{29}$$

which is also unambiguously less than the variance of abatement under the absolute limit, and is less volatile than a fully indexed cap iff

$$\underline{Q} > Q_t Z^{TS}, \tag{30}$$

which is the analogue of eq. (22). Thus, if policy makers set a target to satisfy eq. (30)—which for a given value of Z^{TS} is increasingly difficult due to the increase in BAU emissions—then they should choose $0 < \eta* < 1$, and a fully-indexed intensity cap otherwise. In Figure 1, the effect on the *OJ* locus of setting $\eta = \eta*$ is identical to that described in the previous section.

[8] For more in-depth discussion see Ellerman and Sue Wing, pp. S14-S15.

5. EMPIRICAL TESTS

We now illustrate the practical importance of the foregoing theoretical results by conducting backcasting analyses for several countries. We consider an alternate state of the world in which countries decided to limit their emissions of CO_2 in earlier decades, and investigate what would have been the optimal choice for the form of their emission limits under the criteria developed in the previous section, using historical data on their GDP and emissions.

5.1 Preservation of Expectations

Our first backcasting experiment investigates the setting of a target under the expectations preservation criterion. Recall that our analysis presupposed a future emission limit, whose form depended on the volatility of the series of forecasts of emissions and GDP in the run-up to its entry into force. There is a dearth of historical data on projections of emissions and GDP; however forecasts were conducted annually for a small number of regions by the DOE/EIA for the International Energy Outlook. We focus on the year 2000, for which there are the longest series of comparable historical forecasts over the broadest range of countries. EIA prepared forecasts of emissions and GDP in this year for four developed economies (USA, Japan, Canada and OECD Europe), one economy in transition (the Former Soviet Union—FSU) and two industrializing economies (China and Mexico).[9]

For the target year T = 2000 we employed these country series to compute values for $\rho^f[Q_T, Y_T]$, $v^f[Q_T]$, $v^f[Y_T]$ and Z^{EP}. The results are shown in panel A of **Table 1**. The values of Q^* / Q_T indicate that in order to preserve initial expectations of abatement and associated cost, the levels of abatement which would have to be undertaken for these regions to prefer an intensity cap are quite large: between 25 and 50% of year 2000 baseline emissions in the U.S., Canada, China and Mexico, and over 90% in Japan. Thus, for what would appear to be politically feasible emission limits (less than a ~30% reduction from baseline), the U.S., Japan, Canada, China and Mexico would tend to prefer an absolute cap. On the other hand, for Europe and FSU Q^* / Q_T lies to the right of the so-called “feasible region” in Figure 1 where an emission limit would bind, implying that an intensity cap is preferable.

To test the robustness of these findings we re-compute the values of Q^* / Q_T using data for the year 2010, forecasts of which are available from 1990 onward. The results, shown in panel B, exhibit some important differences. The cutoff values above which an absolute cap is preferable are negative for Japan and Mexico, which points unequivocally to the use of an absolute cap, and exceed unity for Europe and FSU, arguing unequivocally for an intensity cap. The results for the remaining countries are less clear-cut. The levels of abatement which they would have to undertake for an intensity cap to be preferable are 45-55% for USA, 25-35% for Canada and 10-45% for China. Given regions’ Kyoto abatement targets, which we include for comparison, the U.S. would tend to prefer an absolute cap, while Canada could go either way. If China were to reduce its emissions by more than ten% through the CDM or other means, our analysis shows that it would be indifferent to the form of the limit.

[9] The date of the last forecast is 1999 for all of these regions, but the date of the first forecast differs by region. Complete data were available for Canada, Europe, Japan and the U.S. from 1987, for China from 1990, for FSU from 1994, and for Mexico from 1995.

Table 1. The Expectations Preservation Criterion Applied to DOE/EIA Forecasts.

	USA	OECD Europe	Japan	Canada	Former USSR	China	Mexico
				A. $T = 2000$			
$\rho^f[Q_T, Y_T]$	0.297	0.233	0.135	0.158	0.313	0.644	0.192
$v^f[Q_T]$	0.026	0.090	0.127	0.037	0.446	0.061	0.101
$v^f[Y_T]$	0.023	0.031	0.175	0.029	0.147	0.148	0.056
Z^{EP}	0.336	0.670	0.097	0.205	0.947	0.267	0.349
$E_0^f[Q_T]$ [a]	1491	672	284	144	786	840	115
$E^f[Q_T]$ range [a]	1471-1605	672-1235	273-401	143-161	249-810	840-1031	97-123
Q^* [a]	1001	902	55	59	1487	449	80
Q^* range [a]	987-1077	901-1655	53-78	58-65	471-1533	449-551	67-85
Actual Q_T [a]	1619	787	323	119	185	762	116
Q^* / Q_T range	0.61-0.67	1.15-2.1	0.16-0.24	0.49-0.55	2.55-8.29	0.59-0.72	0.58-0.73
$\eta^*\left(\underline{Q}_T / \overline{Q}_T = 0.95\right)$	0.35	0.71	0.10	0.22	1.00	0.28	0.37
$\eta^*\left(\underline{Q}_T / \overline{Q}_T = 0.90\right)$	0.37	0.74	0.11	0.23	1.05	0.30	0.39
$\eta^*\left(\underline{Q}_T / \overline{Q}_T = 0.75\right)$	0.45	0.89	0.13	0.27	1.26	0.36	0.47
				B. $T = 2010$			
$\rho^f[Q_T, Y_T]$	0.597	0.409	-0.042	0.140	0.837	0.575	-0.021
$v^f[Q_T]$	0.036	0.111	0.127	0.047	0.205	0.135	0.091
$v^f[Y_T]$	0.082	0.035	0.209	0.047	0.125	0.208	0.153
Z^{EP}	0.260	1.306	-0.026	0.138	1.379	0.373	-0.012
$E_0^f[Q_T]$ [a]	1819	1101	309	168	1265	944	133
$E^f[Q_T]$ range [a]	1621-1835	982-1385	309-466	160-186	666-1265	944-1523	127-164
Q^* [a]	944	2877	-16	46	3490	703	-3
Q^* range [a,b]	842-953	2566-3619	(24)-(16)	44-51	1837-3490	703-1135	(4)-(3)
Q^* / Q_T range [a,b]	0.48-0.54	2.22-3.14	(0.07)-(0.04)	0.26-0.30	2.17-4.12	0.55-0.89	(0.03)-(0.02)
$\underline{Q}_T / E^f[Q_T]$ Kyoto range [c]	0.68-0.77	0.64-0.91	0.55-0.83	0.63-0.74	0.78-1.49	–	–
$\eta^*\left(\underline{Q}_T / \overline{Q}_T = 0.95\right)$	0.27	1.37	-0.03	0.15	1.45	0.39	-0.01
$\eta^*\left(\underline{Q}_T / \overline{Q}_T = 0.90\right)$	0.29	1.45	-0.03	0.15	1.53	0.41	-0.01
$\eta^*\left(\underline{Q}_T / \overline{Q}_T = 0.75\right)$	0.35	1.74	-0.03	0.18	1.84	0.50	-0.02

[a] Megatons of carbon.
[b] Figures in parentheses indicate negative values.
[c] Kyoto emission targets as specified in DOE/EIA (1998: Table 8).

The results for Mexico and China may seem counterintuitive, but they correctly highlight the fact that intensity targets do not always accommodate growth in ways that tend to preserve initial expectations. The core of the accommodation argument, namely that uncertainty about future economic growth creates the risk of unanticipated high BAU emissions, abatement costs and associated adverse economic impacts at T, appears sound. However, the articulation of this point (*e.g*., by the White House 2002) tends to confuse future *uncertainty* about the baseline with future increases in the *level* of the baseline. The growth rates of GDP and emissions in Mexico and China both exceed those of the U.S., yet the expectations preservation criterion implies that they should employ an absolute cap. This result emphasizes that insofar as policy makers desire to accommodate unanticipated increases in baseline emissions, abatement and costs, their preference among instruments for setting an emission target should be guided by the *interaction* of the level of the target with the relative variability of, and the correlation between, forecasts of BAU emissions and GDP.

A final, striking feature of Table 1 is the large fluctuations in expected BAU emissions in the run-up to the target year. Indeed, actual year-2000 emissions for USA, Canada, FSU and China all lie outside the range of forecasts $E[Q_T]$. Fortunately, however, such volatility turns out not to matter in the present example, as the expectations preservation criterion appears to point decisively to the optimality of either the absolute or the intensity limit. Nevertheless, it is likely that in the run-up to 2010 countries may exhibit values of Z^{EP} sufficiently close to their Kyoto abatement levels that errors in the forecasts make it impossible to choose between an absolute and an intensity limit.

Although this is not the place to critique the accuracy of long-run projections of the emission intensity of GDP (see, *e.g*., Sanchez, 2003; Strachan, forthcoming), the potential difficulty in projecting Q_T and Y_T to the degree of accuracy necessary to choose between intensity and absolute emission limits is worrying. This problem is most consequential in the initial stages of a program to abate CO_2, when the adverse economic consequences of choosing the wrong instrument might have a chilling effect on countries' incentives to pursue deeper cuts. This possibility underscores the need for infrastructural improvements in forecasting technology in advance of such a regulatory program getting under way.

5.2 Temporal Stability of Abatement

Our second experiment focuses on the temporal stability criterion. We investigate whether policy makers would choose an intensity or an absolute emission target to minimize the volatility of abatement and associated costs over a ten-year policy horizon. There is an abundance of data which can be used to study this question. Using statistics on carbon emissions from Marland *et al*. (2003) and real GDP from the Penn World Table 6.1 (Heston *et al*., 2002) we compile a dataset of 30 developed and developing countries over period 1950-2000, from which we compute the terms on each side of eq. (26).

An important source of uncertainty influencing policy makers' choice of instrument under the temporal stability criterion is the time-lags with which pertinent data become available. For example, in OECD countries it is typical for estimates of GDP and emissions to be published with a lag of two years, while in LDCs economic and environmental statistics may take considerably longer to be released. While our data provide the actual values of GDP and emissions, using these data for their corresponding year in a backcasting analysis fails to capture the uncertainty described above, which analysts must deal with by using forecasts based on historical observations to approximate current conditions for which information is not yet available.

Accordingly, in our use of historical statistics we attempt to recreate the kind of prospective assessment which is characteristic of climate policy analysis. We therefore approximate the components of the right-hand side of eq. (26) with a lag of five years, and compute the corresponding statistics over a ten-year period. Thus, for t = 1980, $\rho^h[Q_t, Y_t]$ and the numerators of the coefficients of variation $v^h[Q_t]$ and $v^h[Y_t]$ are computed using data for the period 1965-1975. Moreover, since at any point in time actual GDP and emissions in that particular year will not be known, we approximate the denominators of $v^h[Q_t]$ and $v^h[Y_t]$ using forecasts based on the corresponding estimated rates of growth, *i.e.*,

$$v^h[Q_t] = \frac{\sigma[Q \mid Q_{t-15},...,Q_{t-5}]}{Q_{t-5} \cdot \exp\{5 \cdot E[g_Q^h \mid Q_{t-15},...,Q_{t-5}]\}} \tag{31}$$

and

$$v^h[Y_t] = \frac{\sigma[Y \mid Y_{t-15},...,Y_{t-5}]}{Y_{t-5} \cdot \exp\{5 \cdot E[g_Y^h \mid Y_{t-15},...,Y_{t-5}]\}}, \tag{32}$$

where σ denotes the relevant standard deviation.

Table 2 summarizes the results of this calculation for a selection of countries among the top 20 CO_2 emitters in the year 2000.[10] We present data for three recent years, 1980, 1990 and 1999, which reflect the correlation between, and the relative volatility of, emissions and GDP for the periods 1966-1975, 1976-1985 and 1986-1994 respectively. Most apparent is the strong positive correlation between emissions and GDP for LDCs, and for developed countries before 1975 and after 1985. By contrast, OECD nations exhibit weak or even negative emissions-GDP correlation throughout the decade of high energy prices. The coefficients of variation of emissions and GDP are an order of magnitude smaller and similar in size, and show no trend in the dominance of one type of volatility over the other.[11] Thus, Q^* / Q_t tends to be positive and greater than unity for developed countries for the years 1980 and 1999, and for LDCs in all years, and negative for developed countries in 1990. The upshot is that intensity caps are unequivocally preferable for LDCs, and may be generally preferable for developed countries. The qualification in the latter conclusion arises from the potential for rapid energy price increases to decouple emissions and GDP.

We conduct a more systematic exploration of these outcomes by computing annual values for Q^* / Q_t over the period 1965-1999 on a rolling basis for a sample of 22 developed and 7 developing countries.[12] **Figure 2** presents these results as probability distributions. In both

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[10] We use those countries from Marland *et al.* (http://cdiac.esd.ornl.gov/trends/emis/tre_tp20.htm) for which sufficiently long GDP time-series are available. Problems with the Penn World Table GDP data forced us to drop key emitters such as Germany, Saudi Arabia, Russia and Ukraine.

[11] The exceptions are India, South Korea and Mexico, whose emissions are persistently more variable than their GDP.

[12] The OECD country panel (N = 790) is made up of Australia, Austria, Belgium, Canada, Denmark, Finland, France, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, UK, and USA. The developing country panel (N = 247) is made up of Brazil, China, India, Mexico, South Korea, South Africa, and Turkey.

Table 2. The Temporal Stability Criterion Applied to Historical Data.

	Year	$\rho^h[Q_t, Y_t]$	$v^h[Q_t]$	$v^h[Y_t]$	Z^{TS}	Q^* (MTC)	$E[Q_t]$ (MTC)	Actual Q_t (MTC)	Q^* / Q_t [a]
					Developed Countries				
USA	1980	0.929	0.064	0.070	0.847	2470	1458	1300	*1.900*
	1990	-0.276	0.031	0.063	-0.136	-393	1444	1374	**-0.286**
	1999	0.979	0.041	0.061	0.668	2241	1676	1567	*1.430*
Japan	1980	0.994	0.163	0.113	1.442	819	284	251	*3.259*
	1990	-0.046	0.026	0.071	-0.017	-10	286	292	**-0.033**
	1999	0.970	0.069	0.080	0.831	592	356	315	*1.877*
U.K.	1980	0.365	0.026	0.050	0.186	75	203	158	0.476
	1990	-0.583	0.053	0.044	-0.698	-242	173	155	**-1.555**
	1999	0.082	0.044	0.055	0.066	22	171	147	0.153
Canada	1980	0.944	0.092	0.094	0.916	234	128	115	*2.041*
	1990	0.119	0.029	0.067	0.051	13	124	113	0.111
	1999	0.860	0.041	0.049	0.719	207	144	120	*1.725*
Italy	1980	0.987	0.110	0.080	1.358	294	108	102	*2.893*
	1990	0.095	0.027	0.055	0.046	10	112	106	0.097
	1999	0.934	0.042	0.063	0.622	151	122	116	*1.311*
France	1980	0.954	0.083	0.090	0.886	261	147	132	*1.984*
	1990	-0.813	0.103	0.051	-1.658	-393	118	99	**-3.988**
	1999	-0.170	0.045	0.058	-0.131	-27	104	100	**-0.274**
Australia	1980	0.976	0.075	0.083	0.893	100	56	55	*1.801*
	1990	0.885	0.059	0.060	0.866	121	70	73	*1.670*
	1999	0.969	0.069	0.068	0.979	178	91	94	*1.896*
Spain	1980	0.979	0.155	0.101	1.510	170	56	55	*3.114*
	1990	-0.142	0.032	0.022	-0.209	-25	60	58	**-0.431**
	1999	0.869	0.073	0.073	0.866	118	68	75	*1.567*
					Developing Countries				
China	1980	0.983	0.180	0.092	1.909	1447	379	403	*3.590*
	1990	0.939	0.097	0.119	0.764	935	612	655	*1.428*
	1999	0.963	0.093	0.117	0.764	1424	932	771	*1.847*
India	1980	0.896	0.084	0.075	1.010	172	85	95	*1.816*
	1990	0.990	0.122	0.094	1.285	394	153	184	*2.138*
	1999	0.992	0.126	0.093	1.353	733	271	294	*2.494*
South Korea	1980	0.992	0.173	0.119	1.436	75	26	34	*2.202*
	1990	0.952	0.127	0.107	1.128	120	53	66	*1.817*
	1999	0.981	0.156	0.110	1.399	302	108	107	*2.813*
Mexico	1980	0.994	0.126	0.104	1.200	119	49	69	*1.721*
	1990	0.971	0.143	0.105	1.325	227	86	102	*2.212*
	1999	0.891	0.125	0.072	1.559	381	122	113	*3.383*
South Africa	1980	0.957	0.088	0.103	0.816	99	60	58	*1.711*
	1990	0.929	0.107	0.072	1.381	241	87	78	*3.087*
	1999	0.652	0.030	0.030	0.668	132	98	91	*1.449*
Brazil	1980	0.996	0.156	0.126	1.233	114	46	50	*2.285*
	1990	0.334	0.049	0.067	0.243	27	55	55	0.482
	1999	0.880	0.062	0.038	1.426	211	74	83	*2.551*

[a] Bold text indicates that absolute caps are unambiguously preferable, italics indicate that intensity caps are unambiguously preferable.

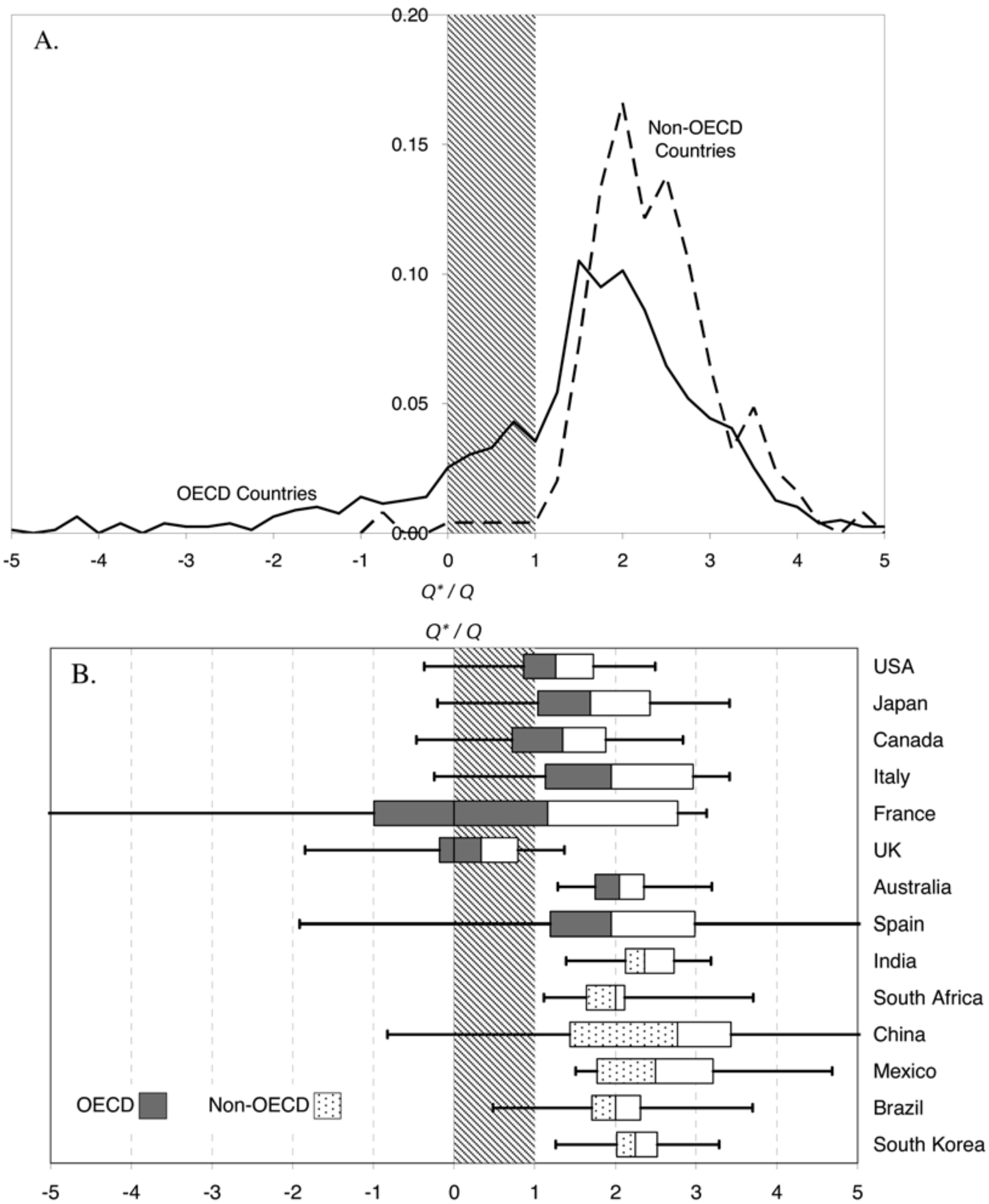

Figure 2. The Temporal Stability Criterion: Probability Density Functions.
A. Global aggregates. B.High-emitting countries.

panels, the shaded region corresponds to the feasible range of abatement. In panel A, the bulk of the probability masses of both developed and developing countries lie to the right of the feasible region.[13] In terms of the geometry of Figure 1, this means that the point K lies completely to the right of the 0-1 scale, so that binding emission limits will tend to be positioned to its left. These

[13] The probability of Q^* / Q_t being less than unity is 28% for OECD countries and only 3% for non-OECD countries, while the probability of it being negative is 14% for OECD countries and only 1.2% for non-OECD countries. As in **Table 2**, the long lower tail of the distribution for OECD countries reflects the influence of the period of high energy prices from 1974-84, and the consequent negative correlation between emissions and GDP over this period.

results echo our previous findings, and imply a clear preference for the use of intensity limits, especially in LDCs.

The box plot in Panel B illustrates the substantial inter-country heterogeneity which underlies the foregoing conclusion. While the entire probability distributions of Q^* / Q_t for India, South Africa, Mexico and Korea lie to the right of the feasible region, portions of the first quartiles of the distributions for Brazil and especially China overlap with the feasible region, indicating that in some (albeit rare) circumstances these countries might prefer an absolute cap. Even among developed countries, the means of the distributions of Q^* / Q_t almost always exceed unity, again indicating the desirability of intensity limits. Nevertheless, their lower quartiles intersect the feasible region and the negative orthant to a greater degree than is the case for the LDCs, indicating the higher probability of an absolute cap being preferred, especially in countries such as France and the U.K.

5.3 Preserving Expectations vs. Minimizing Temporal Volatility: Tradeoffs and Implications

The foregoing results highlight the potential for the expectations preservation criterion and the temporal stability criterion to yield conflicting prescriptions for a country's choice of the form of emission limit. In light of this phenomenon, it is natural to ask which type of cap policy makers should choose. However, in previous work we emphasize that the necessity of selecting either an absolute or an intensity limit is a false dichotomy, which may be alleviated by specifying emission targets as hybrid caps with incomplete indexation (Ellerman and Sue Wing, 2003). Below, we illustrate that for plausible emission targets there may be much greater agreement between the optimal values of the indexation parameter, η^*, computed under the two criteria.

Table 1 shows the values of η^* for the expectations preservation criterion calculated using eq. (20) assuming cuts in emissions of five, ten and 25% below BAU levels. For the year 2000 the optimal values of the indexation parameter range from 0.1-0.2 for Japan, 0.2-0.5 for USA, Canada, China and Mexico, 0.7-0.9 for Europe and greater than one for FSU. For 2010, η^* is negative for Japan and Mexico, lies in the same range of values for the U.S., Canada and China as in 2000, and is greater than unity for Europe and FSU. The implication is that hybrid emission limits with varying degrees of indexation are the instrument of choice for the majority of countries, with intensity caps being strictly preferred in Europe in 2010 and in Russia, and absolute caps being strictly preferred only by Japan and Mexico in 2010.

The results for optimal indexation under the temporal stability criterion are broadly similar, though the values of η^* differ somewhat for each country. The box plots in **Figure 3** show the probability distributions of η^* calculated using eq. (28) for the panel of countries in Section 5.2. For emission targets set at 95 and 75% of baseline levels, the bulk of the probability masses for large LDC emitters lies to the right of the range of feasible values of η^* (denoted by the shaded area), indicating that, on average, these countries uniformly prefer fully-indexed intensity caps. Although the probability distributions of OECD countries overlap the feasible region to a greater degree, the results are similar for Australia, Spain and Italy. Mean values of η^* for the remainder of the OECD range from 0.1 in France and the U.K. to 0.6-0.9 for Canada and the U.S., and 0.9-1 for Japan, implying a general preference for partially indexed caps.

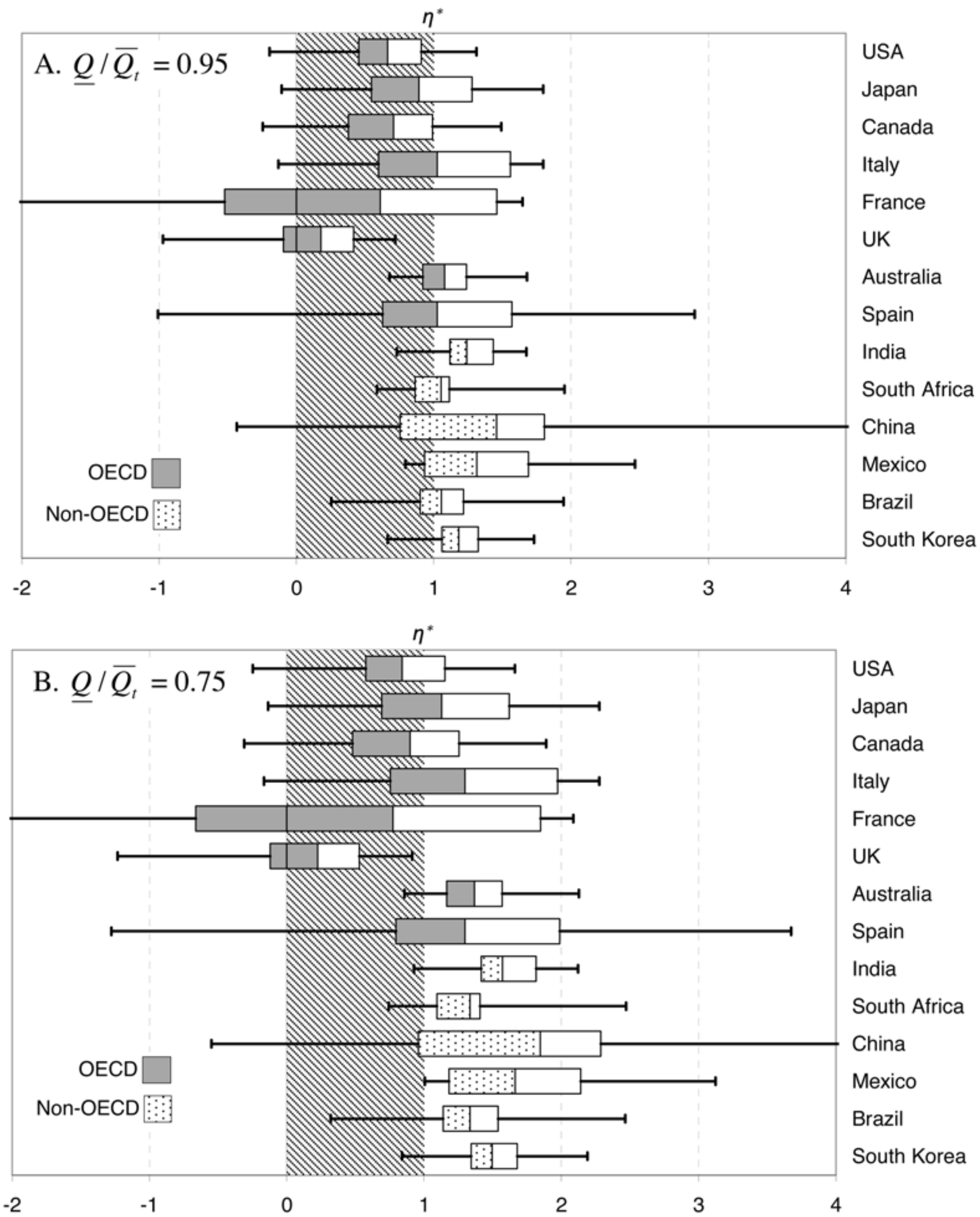

Figure 3. Optimal Indexation Under the Temporal Stability Criterion.

Japan and Mexico are examples of economies where the criteria continue to give conflicting recommendations, even under optimal indexation. For most countries it is the case that while the elements of the pairs of variables $v^f[Q]$, $v^h[Q]$ and $v^f[Y]$, $v^h[Y]$ have similar magnitudes, the difference in the values of Z^{EP} and Z^{TS} originates in the divergence between the emissions-GDP correlation over time, ρ^h, versus across forecasts, ρ^f. The latter correlation is generally much weaker, reflecting the updating of expectations as new data become available. The value of ρ^f is particularly low in both Japan and Mexico, and is *negative* for the year 2010.

The way forward in situations where this kind of conflict arises will depend on the evolution of the architecture of international climate agreements. On one hand, if the current targets-andtimetables structure is retained, resulting in a sequence of agreements to undertake one-shot commitments, then the relevant uncertainty will continue to be the expectation of BAU emissions in the discrete period when the cap under negotiation is enters into force, not the relative volatility of emissions and GDP over a span of multiple commitment periods. In this circumstance it makes sense for a country to adopt the form of the limit prescribed by the expectations preservation criterion.[14] One the other hand, if the architecture evolves to admit longer commitment periods or trajectories of emission targets for abating countries, then it is preferable for a country to follow the prescriptions of the temporal stability criterion.

6. CONCLUSION

In this paper we elucidated the differences between absolute and intensity-based caps on CO_2 emissions under uncertainty. We demonstrated that fixed and flexible caps are identical when there is no uncertainty about the future, and analyzed the choice between these forms of an emission target using two criteria for judging their relative attractiveness under uncertainty: expectations preservation—the minimization of the difference between the actual level and the initial forecast of abatement and compliance costs associated with a one-shot emission target, and temporal stability—the minimization of the variance of abatement due to fluctuations in emissions and GDP over time.

The main results of the paper are mathematical statements of the conditions under which one or the other form of the limit is preferable, and our empirical tests of these propositions using data on nations' CO_2 emissions and GDP. Our principal finding is that intensity caps are preferable to absolute caps for a broad range of emission targets, a conclusion which is robust for less-developed countries, but is more equivocal for developed economies. We also find the potential for the aforementioned criteria to give rise to conflicting prescriptions for which type of policy instrument should be used. We show that the resolution of such conflicts hinges primarily on countries' ability to specify their emission targets as partially-indexed caps, which are generally preferred. Finally, where such a reconciliation is not possible, we argue that a practical solution is for policy makers to rely on the prescriptions of the criterion which is more congruent with the character of the architecture for international climate negotiations.

Acknowledgements

ISW was supported by U.S. Department of Energy Office of Science (BER) Grant No. DE-FG02-02ER63484. ADE and JMS were supported by the MIT Joint Program on the Science and Policy of Global Change, funded through a government-industry partnership including U.S. Department of Energy Office of Science (BER) Grant No. DE-FG02-94ER61937, U.S. Environmental Protection Agency Cooperative Agreement No. XA-83042801-0, and a group of corporate sponsors from the U.S. and other countries. This paper has benefited from helpful comments by Jake Jacoby, John Reilly, John Parsons, Dick Eckaus, and participants at the Cambridge-MIT Electricity Policy Forum Spring Research Seminar and the EPRI Global Climate Change Research Seminar. Errors and omissions are solely the authors' responsibility.

[14] Note, however, that rolling negotiations give countries the flexibility to readjust the form of the limit to suit their expectations of the relative volatility of their emissions and GDP, commitment period by commitment period.

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