MIT Joint Program on the Science and Policy of Global Change

Adjustment time, capital malleability and policy cost*

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To inform processes of policy development and implementation, climate change research needs to focus on improving the prediction of those variables that are most relevant to economic, social, and environmental effects. In turn, the greenhouse gas and atmospheric aerosol assumptions underlying climate analysis need to be related to the economic, technological, and political forces that drive emissions, and to the results of international agreements and mitigation. Further, assessments of possible societal and ecosystem impacts, and analysis of mitigation strategies, need to be based on realistic evaluation of the uncertainties of climate science.

This report is one of a series intended to communicate research results and improve public understanding of climate issues, thereby contributing to informed debate about the climate issue, the uncertainties, and the economic and social implications of policy alternatives.

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Adjustment Time, Capital Malleability and Policy Cost

*Henry D. Jacoby and Ian Sue Wing**

The cost of meeting Kyoto-style emissions reductions is heavily dependent on the malleability of an economy's stock of capital and the number of years available for adjustment. Each year of delay introduces more emission-producing activities that must be squeezed out of the system and shortens the time horizon for change, raising the carbon price required to produce the needed changes in capital structure. The MIT Emissions Prediction and Policy Assessment model is used to explore the effects of uncertainty in the degree of capital malleability in the short run, and to analyze how implied carbon prices vary depending on the time of credible commitment to emissions targets.

INTRODUCTION

Emissions reductions of the magnitude foreseen in the Kyoto Protocol would require large changes in the structure of production and consumption in Annex I countries, a challenging task even if attempted over a period of decades. With each succeeding year of dispute, deliberation and negotiation, the window to achievement of these proposed targets progressively closes. The shorter the time period over which the control task would be undertaken the higher the expected short-run cost, until at some point the targets lose credibility even with strong political commitment. One key influence on the level of difficulty is the rate at which the capital stock can be either replaced or retrofit, in order to sustain economic activity with a less carbon-intensive input mix.

For analysis of greenhouse gases, especially CO_2, our focus naturally is on energy as an input to economic activity, and in particular on the various forms of fossil energy. Energy is not used by itself, of course, but in the form of energy services supplied with the aid of some capital device. To some degree these two inputs can be substituted for one another in providing these services (e.g., a more costly but more efficient air conditioner). Further substitution is possible among the various sources of primary energy (oil, gas, coal, nuclear,

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etc.) and between energy and capital and other inputs such as labor and non-energy materials. The cost of reducing emissions from fossil fuel use depends importantly on the ease of substitution among these various inputs to production. For purposes of our analysis we frame this issue of economic adjustment in terms of the "malleability" of an economy's capital stock, defined in terms of the relative ease or difficulty of changing the proportions of these factors as they are combined in productive processes.

Market economies, like those that make up most of Annex I, will seek a least-cost mix of these input factors. Historically, CO_2 emissions have been priced at zero, so we inherit a capital structure whose technology and design were selected without regard to this byproduct of energy use. Moreover, most nations appear set to continue for some years applying energy- and emissions-intensive production techniques, further developing their economies along a zero-carbon-price trajectory despite their participation in the Climate Convention. We are already at the brink of the millenium, however. If and when actions are taken to meet the 2008-2012 Kyoto targets, the window for structural change will be short relative to the normal time of capital stock turnover in many sectors.

Of course, it is not necessary to wait-out the "normal" life of capital assets (i.e., an adjustment period consistent with stable long-run energy prices). We can speed-up the process through the retrofit of existing capital assets, and by under-utilizing the worst of the existing facilities or abandoning them before the end of their useful life. To the degree that change by this route is limited, however, reductions must come through ever higher expenditure on emissions-reducing features of facilities and equipment installed in new investment, and through reductions in the consumption of energy services (a process with its own rigidities in the short run). The more rapidly the emissions reduction is attempted the higher the actual (or implicit) carbon price must rise to bring about the required adjustments.

Here we consider these issues of economic adjustment with a focus on two determinants of the difficulty of the task, both yet to be determined: how soon nations will commit to the implied emissions controls, and whether emissions permit trading will play a significant role in Protocol implementation.

THE CHALLENGE OF MODELING SHORT-TERM ADJUSTMENT

The process of capital adjustment under policy pressure is not well understood. Although much effort has gone into analysis of the productivity effects of the energy price shocks of the 1970s (Berndt and Wood, 1987), studies of the potential effects of carbon policies imposed over periods as short as a few years have begun only recently. For example, several of the models discussed in this volume were designed to assess alternative patterns of emissions controls spanning several decades, or to study the stabilization of atmospheric CO_2 concentration over periods of 150 years or more (Jacoby, Reiner and Schmalensee, 1997; Jacoby, Schmalensee and Sue Wing, 1998; Manne and Richels, 1992, 1997). The Emissions Prediction and Policy Assessment (EPPA) model which we use below is a descendent of the General Equilibrium Environment (GREEN) model (Burniaux, 1992) which was applied by the OECD to analyses covering the period 1985 to 2050. Among other changes in its adoption at MIT the model was extended to 2100, for computation of greenhouse gas scenarios applied in integrated studies of economic and climatic effects (Prinn et al., 1998). Other models which have a similar multi-region, multi-sector representation of the world economy are applied on EPPA's century horizon (e.g., Edmonds et al., 1995), or over even longer periods (e.g., Manne, Mendelsohn, and Richels, 1995).

As negotiations proceed under the Climate Convention, and particularly with the specification of the emissions targets in the Kyoto Protocol, the interest of both policymakers and the public is shifting from longer-term climate issues to the consequences of emissions controls in the near term. This shift in emphasis imposes new and difficult demands on these economic modeling efforts. Naturally, no model can do everything well, and different analysis groups have pursued diverse objectives when formulating the models currently used in climate change policy analysis.

Three characteristics of these models are important in application to analysis on the time horizon of the Kyoto targets. The first and most obvious is the time-step on which a model solves. Several models use a ten-year time step which limits their ability to analyze phenomena occurring within a decade, such as the consequences of accepting a 2008-2012 Kyoto target only some time after the year 2000. The results of such models may thus obscure important short-run dynamics of adjustment.

The second attribute is the level of detail in modeling the capital stock and the production structure, which affects how models represent the sources of rigidity in the production sectors of the economy. Models that assume a fully malleable capital stock (in which inputs are fully fungible, a so-called putty-putty specification) are less able to capture the difficulties of short-term adjustment of the energy economy than those with an engineering-process representation of the energy technologies (e.g., Manne and Richels, 1992). Models in the former category based on the constant-elasticity-of-substitution (CES) or other aggregate production functions frequently rely on elasticities of substitution that gradually increase over the modeling horizon to distinguish between short- and long-term adjustment. Through this contrivance factor substitution is made more difficult in the short run, thereby approximating the effects of both the short-term aggregate rigidity of capital, and the long-run increase in substitution possibilities due to technical progress.

The third characteristic is the specification of economic behavior as forward-looking or myopic. Intertemporal models assume that agents with perfect foresight solve for the path of emissions reductions that minimizes discounted cost over the entire modeling horizon, choosing the timing and stringency of control measures so as to optimally smooth the costs of adjustment. By contrast, myopic models assume that economic agents seek to minimize the costs of policy on a period-by period basis, and take little or no action in advance of the onset of carbon constraints. For a given level of rigidity in the economy, the latter behavior thus creates the possibility of a bunching of investment in measures to control emissions, leading to higher short-run costs.[1]

Here we use the MIT EPPA model (Yang et al., 1996) to study these issues of short-run adjustment to policy pressure.[2] This model keeps track of capital by vintage, with capital retaining some substitutability of inputs post investment (which may be thought of as retrofit). This feature provides a capacity to investigate the ease of adjustment to policy restriction and issues of timing. The model experiments are intended to serve two purposes. First of all, we seek insight into climate policy issues, particularly the influence of the timing of ratification and start of serious policy action on the climate issue. But we also explore general issues that arise in using computable general equilibrium (CGE) models to study the pace of adjustment in response to policy change.

The start of serious carbon-saving action and the path of subsequent reductions will be determined by expectations as to when nations will commit to the proposed targets, and the credibility of these commitments once declared. Because EPPA is a myopic model, the analysis of expectations, credibility and response must be conducted outside the model and imposed via a set of simple scenarios. Our procedure is suggested by the structure of the Kyoto Protocol, whose provisions go into effect only when countries representing 55 percent of 1990 Annex I emissions have ratified the agreement. We treat this date as the point of credible commitment, when carbon restrictions are applied, and refer to it as the time of "ratification." Further, we assume that greenhouse gas controls imposed before this time, in expectation of ratification, will not be so large as to invalidate the insights gained here and so can be ignored.

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[1] Other studies with a short-term focus use an econometric approach, or a hybrid of econometric and other methods. Examples include a study by the Energy Information Administration (1998a) using the National Energy Modeling System (Energy Information Administration, 1998b), and work by the Wharton Econometric Forecasting Associates (1997) employing a model based on Klein et al. (1995).

[2] The EPPA model has been developed with the support of a government-industry partnership that includes the U.S. Department of Energy (901214-HAR; DE-FG02-94ER61937; DE-FG02-93ER61713), U.S. National Science Foundation (9523616-ATM), U.S. National Oceanic and Atmospheric Administration (NA56GP0376), and U.S. Environmental Protection Agency (CR-820662-02), and a group of corporate sponsors from the United States and other countries.

This last assumption is a crude approximation. It gives insufficient credit to actions already being taken in some counties, even in advance of ratification, and to efforts to organize programs of credit for early action.[3] Given the 55 percent requirement, however, the Protocol cannot enter into force without ratification by the United States. Considering the great uncertainty introduced by the U.S. Constitutional provision which puts ratification in the hands of a Senate independent of the Administration, it seems a reasonable assumption that, in the U.S. at least, the expected magnitude of future policy constraints on greenhouse gases will be low in advance of actual Senate approval. Moreover, it is likely that issues of national competitiveness will limit activity by other nations in advance of substantive actions by the U.S.

After a description of the EPPA model, with a particular focus on its representation of the capital stock, we turn to its application to analysis of the influence of capital malleability on required carbon prices and the effect of the length of wait before commitment to the 2008-2012 targets.

CAPITAL RIGIDITY IN A CES FRAMEWORK

Structure of the EPPA Model

EPPA is a recursive-dynamic CGE model solved on a five-year time step. In the model the world is divided into 12 regional economies, as shown in Table 1. Each region is represented by eight production sectors and four consumption sectors, listed in Table 2, with savings and consumption choices made by a representative agent. Regions are linked by bilateral trade in energy and non-energy producer goods, with the representative agents maximizing regional utility subject to the constraint that supply equal demand in all markets, and that productive factors be fully employed. The model is calibrated to a 1985 benchmark data set and then solved recursively for a sequence of static equilibria. Factor endowments are updated at each step, according to assumed exogenous trends in rates of population growth, increases in labor productivity, autonomous energy efficiency improvement (AEEI), and availability of natural resources (Yang et al., 1996).

For the purposes of the present study, each economy is modeled as having two forms of capital in any period. One portion of the aggregate capital stock is old capital that is fixed in its input proportions, the other is malleable in that its mix of inputs can be altered in response to changing relative prices. Associated with each type of capital is a sub-model that represents the

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[3] EPA's voluntary climate change programs are an example of early action. For an assessment of their performance, see General Accounting Office (1997).

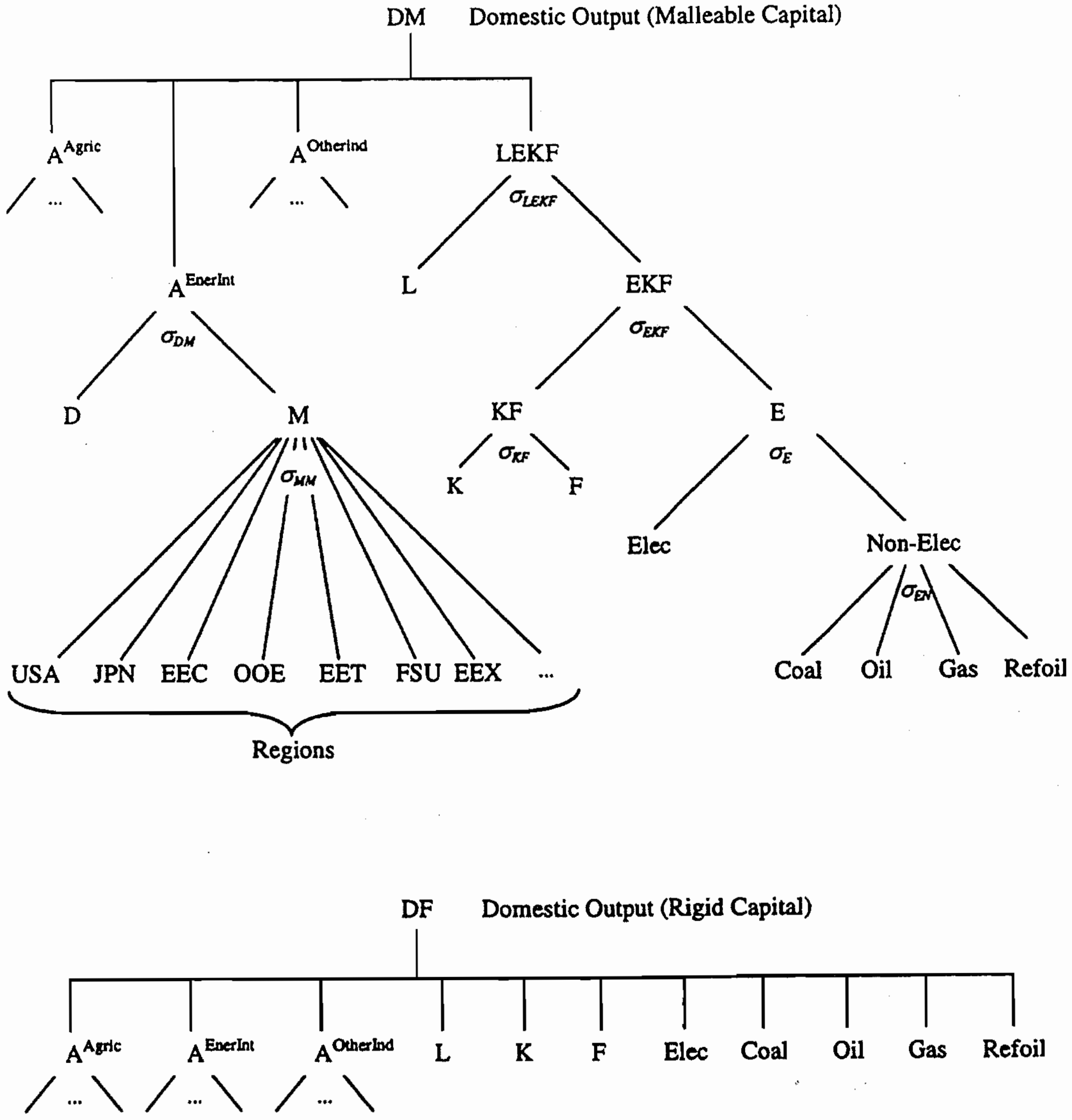
Table 1. EPPA Regions

	Annex I
USA	United States
JPN	Japan
EEC	European Union: Belgium, Denmark, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, UK
OOE	Other OECD nations: Australia, Canada, New Zealand, the European Free-Trade Area (excluding Switzerland and Iceland), and Turkey
EET	Eastern European economies in transition: Bulgaria, Czechoslovakia, Hungary, Poland, Romania, and Croatia/Slovenia
FSU	Former Soviet Union: Russia and Ukraine
	Non-Annex I
EEX	Energy-exporting developing countries: OPEC states as well as other nations exporting oil, gas, and coal
CHN	China
IND	India
BRA	Brazil
DAE	Dynamic Asian Economies: Hong Kong, Philippines, Singapore, South Korea, Taiwan, and Thailand
ROW	Rest of World

Table 2. EPPA Sectors

Production		**Consumption**	
AGRIC	Agriculture	**FOODBEV**	Food and beverages
COAL	Coal	**ENERGY**	Final demand for energy
OIL	Crude oil	**TRNSCOMM**	Transport and communications
GAS	Natural gas	**OTHER**	Non-essential commodities
REFOIL	Refined oil		
ELEC	Electric Power		
ENERINT	Energy-intensive industries		
OTHERIND	Other industries		

Figure 1. EPPA Production Structure for Malleable and Fixed Capital



transformation of primary factors (labor, capital, and resources) and intermediate inputs (including energy) into outputs of the production sectors shown in Table 2. (These goods are then combined into the consumer goods in the table.) The two formulations are shown in Figure 1. In the upper part of the figure is the sub-model (DM) which represents the malleable part of the production structure. Output is modeled by a set of nested CES production functions. With exception of oil and gas, which are treated as perfect substitutes across regions, each of the intermediate goods is an Armington bundle of domestic and imported components (A). Intermediate goods are then combined with capital (K), labor (L), resources (F), and energy (E), nested as shown in the figure. The substitution elasticities in this part of the production structure are fixed at levels appropriate for long-term adjustment to the prevailing factor prices (Yang et al., 1996).[4]

The second part of the structure (DF) is shown in the lower part of Figure 1. It is represented by a series of Leontief production functions, capturing the "rigid" (fixed input proportions) component of the capital stock. The larger the share of sectoral output that originates in the rigid portion of the production structure, the less substitutable are other inputs for fossil fuels at the level of the various sectors and the aggregate economy, and the greater is the inertia of the energy-carbon system. The distribution of aggregate capital between the DM and DF structures therefore strongly affects EPPA's short-run response to pressures on fossil fuel use resulting from emissions reduction quotas.

Vintage Structure and Capital Malleability

The dynamic updating of the capital stock in each region and sector is determined within the capital "vintaging" procedure whereby in each period a fraction of the malleable capital is "frozen" to become part of the rigid Leontief portion.[5] Letting K^m represent the malleable portion of capital and K^r the rigid portion, the procedure can be described as follows. New capital installed at the beginning of each period starts out in a malleable form (DM in Figure 1). By the end of the period a portion ϕ of this capital becomes fixed with the prevailing techniques of production (DF in Figure 1), thereby losing its capacity to be substituted for other inputs. As the model steps forward in time it preserves v vintages of such rigid capital, each retaining the (fixed) coefficients of factor demand that prevailed in the malleable portion of the capital stock when it was frozen in place v periods ago. (Currently, $v = 1,\ldots,4$.) As rigid capital gets older its value of v increases, which determines the amount of this capital remaining each period after depreciation.

The evolution of capital over time is implemented in a set of dynamic equations. The total capital stock in period $t+1$ is the sum of new investment (unproductive in period t), old capital that remains malleable, and v vintages of old (fixed) capital,

[4] Among the substitution elasticities, policy cost is most sensitive to σ_{EN} and σ_{EKF}. In the calculations below these values are 1.0 and 0.7 respectively, and equal across regions.

[5] OIL and GAS are omitted from the vintaging procedure for reasons of computational efficiency. They are treated as Heckscher-Ohlin goods (i.e., perfect substitutes across regions), implying that the model would have to be solved for a unique international price to clear the market in every vintage of these two sectors simultaneously across all 12 regions, a time-consuming procedure. The omission does not substantively alter the character of the results.

$$K_{t+1} = I_t + (1 - \phi)(1 - \delta)K_t + \phi\sum_{v}(1 - \delta)^v K_{t+1-v} \tag{1}$$

The rigid capital is calculated as the partially-depreciated components of malleable capital frozen in previous periods:

$$\begin{aligned} K^r_{t+1} &= \phi(1 - \delta)K^m_t + \phi(1 - \delta)^2 K^m_{t-1} + \phi(1 - \delta)^3 K^m_{t-2} + \ldots \\ &= \phi\sum_{v}(1 - \delta)^v K^m_{t+1-v} \end{aligned} \tag{2}$$

Here vintage $v = 1$ is comprised of capital frozen in the previous period (t), which is a proportion ϕ of the depreciated value of the malleable capital in that period. Older vintages ($v = 2, 3, 4$) simply depreciate over time, frozen in the Leontief structure of their vintage year. Depreciation rates (δ), which are calculated from the base data set, differ across regions. For the Annex I regions of interest here, the annual rates of depreciation vary from 4% for the EEC to 7% for the FSU.

Malleable capital in period $t+1$ then consists of the new investment, I_t, plus a share $(1 - \phi)$ of the last period's malleable capital, whose input proportions can still be changed:

$$K^m_{t+1} = I_t + (1 - \phi)(1 - \delta)K^m_t . \tag{3}$$

The fraction $(1 - \phi)$ can be thought of as that proportion of previously-installed malleable capital which is able to be retrofit to adjust its input proportions to current input prices, and take advantage of intervening technical developments.[6] Examples of retrofit activity, in the face of generally rising carbon and energy prices, include the re-powering of electric generating facilities (say, converting from coal to natural gas), insulation of existing buildings, improvement of the instrumentation of existing equipment, and general improvement of maintenance and management practices. This simple formulation ignores the fact that retrofit itself requires resources, and that the costs of retrofitting are likely to rise the more drastic the adjustment of the capital stock attempted. Thus we implicitly assume that this cost is small compared to the overall bundle of inputs to production, and so can be ignored. In addition, the opportunities for altering

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[6] In this process once investment takes place, malleable capital in one sector cannot be shifted to another. That is, for each sector and region $K^m_{t+1} \geq (1 - \phi)(1 - \delta)K^m_t$. Inter-sectoral capital mobility is likely to be severely limited in practice.

existing capital also are likely to differ across regions, and especially across sectors. However, for the sake of simplicity and to facilitate comparison we assume uniformity of this parameter in both dimensions.

This retrofit or renewal aspect of capital dynamics appears to be neither systematically investigated nor well understood, which is problematic because it represents a large (and as we shall see, potentially important) uncertainty in the analysis of emissions control policy. It significance is raised by the fact that carbon-induced increases in energy prices are likely to be manifest over a decade or less. This is a short time in relation to the normal turnover in energy-using capital stock, but long in terms of the potential for modification of existing capital.

Reference Emissions Forecasts

There are many sources of uncertainty in future emissions (Webster, 1997). Here we focus on the influence of ϕ, the proportion of the capital stock that becomes frozen in each period.[7] This malleability parameter has two opposing effects on emissions growth. On the one hand, the Leontief technology characterizing the rigid portion of the production structure prevents adjustment in the mix of inputs per unit of output in response to changing relative input prices. Technical progress (through the AEEI) thus continually increases the energy efficiency of the malleable part of the capital stock by reducing its unit energy demand, but the rigid part remains unchanged in this characteristic. If surviving capital is completely malleable ($\phi = 0$) emissions *per unit output* are at their lowest, because the energy economy as a whole both adjusts completely to changing prices and fully adopts state-of-the-art technology in every period. The higher the value of ϕ the less complete the adjustment, and the higher the emissions per unit of output.

On the other hand, the reduction in the energy demand of malleable capital through action of the AEEI enables an increasing share of the energy endowment of each representative agent to be re-allocated to alternative productive uses within the economy, which facilitates more rapid growth of output. Thus the more malleable the economy the greater the quantity of energy inputs that will be freed up by increased efficiency, and the higher the growth of output, saving, and capital accumulation. By contrast, the larger the

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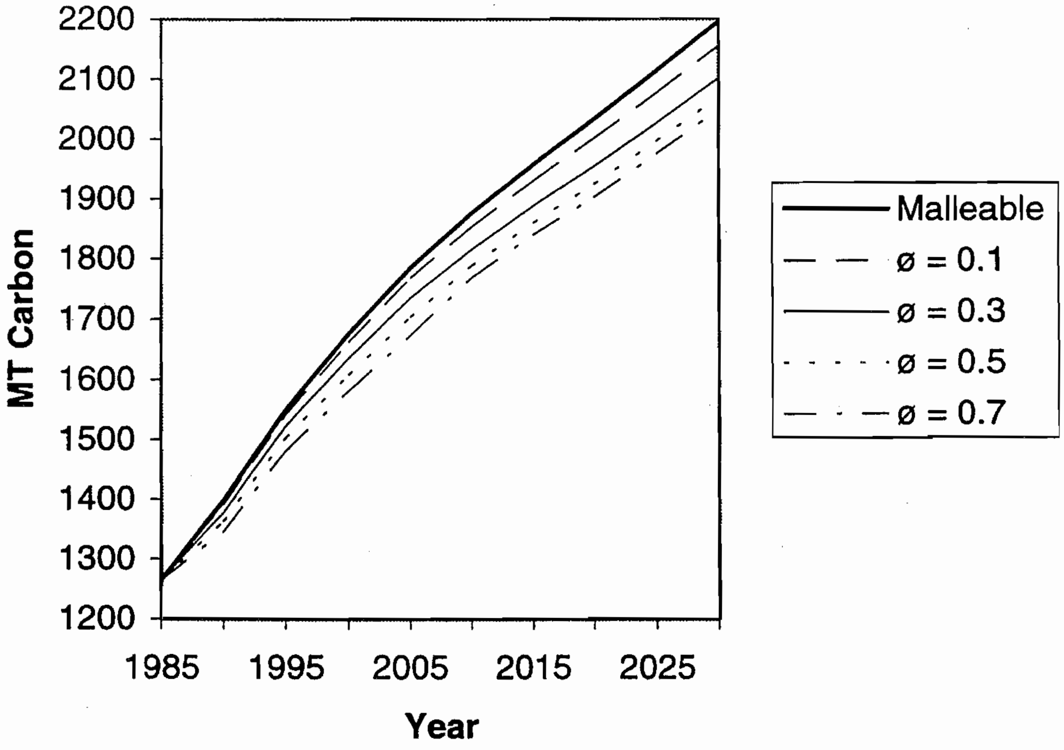
[7] The EPPA model was originally formulated to analyze long-run effects of policy, and previous studies (e.g., Jacoby et al., 1997) initialized ϕ in the base period, after which it declined linearly to zero over a number of periods. In simulations to 2100 this procedure enabled EPPA to reflect the increasing malleability of aggregate capital with time while retaining fixed elasticities of substitution. The results shown here differ somewhat from those derived from earlier versions of the model.

proportion of capital that remains frozen at the factor proportions appropriate to input prices in previous periods the smaller the faction of productive capacity at the best-practice energy-efficiency frontier, and the slower the rate of economic growth.

Because the time path of emissions depends on the relative magnitudes of these two opposing influences, the algebraic sign of the combined effect of greater capital rigidity on emissions cannot be determined *a priori*. The reference forecasts that result from varying levels of capital malleability are shown in Figure 2. They indicate that, in the EPPA model, the attenuating effect of the more rigid capital stock on economic growth outweighs its amplifying effect on the emissions intensity of production, leading to higher emissions the more malleable the capital stock.

Figure 2. Influence of Capital Malleability on USA Reference Emissions



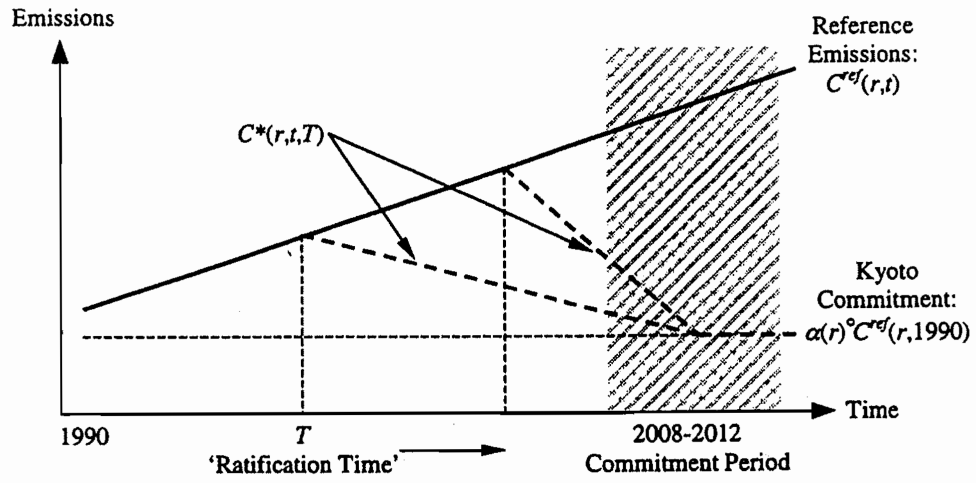
Formulation of Policy Experiments

Policy scenarios for study of the Kyoto Protocol are formulated as follows. Under the agreement each Annex I region r undertakes an emissions reduction commitment of $\alpha(r)$ times its 1990 reference level of greenhouse gas emissions $C^{ref}(r, 1990)$, where for example $\alpha = 0.93$ for the USA. How fast a region's emissions are cut to its Kyoto commitment level is governed by the length of time between the date at which it begins to reduce emissions (i.e., "ratification") and the Kyoto commitment period. Here we approximate the 2008-2012 commitment period by the emissions and costs of the middle year, 2010. Denoting T as the date of such initial actions, we assume that over the period $T < t < 2010$ cuts in emissions are undertaken as a linearly increasing fraction $\beta(T, t)$ of the widening gap between each region's business-as-usual emissions in period t, $C^{ref}(r, t)$, and its eventual commitment level. During this interim period, Annex I carbon quotas, $C^*(r, t, T)$, for various values of T are calculated as

$$C^*(r, t, T) = C^{ref}(r, t) - \beta(T, t) \left[C^{ref}(r, t) - \alpha(r) C^{ref}(r, 1990) \right] , \qquad (4)$$

where $1 \geq \beta(T, t) > 0$. Figure 3 illustrates the general idea. The results presented below explore the implications of different values of the start-date T, and alternative levels of the malleability parameter ranging from $\phi = 0.1$ to $\phi = 0.7$.

Figure 3. Carbon Reduction Profiles for Alternative Dates of Ratification

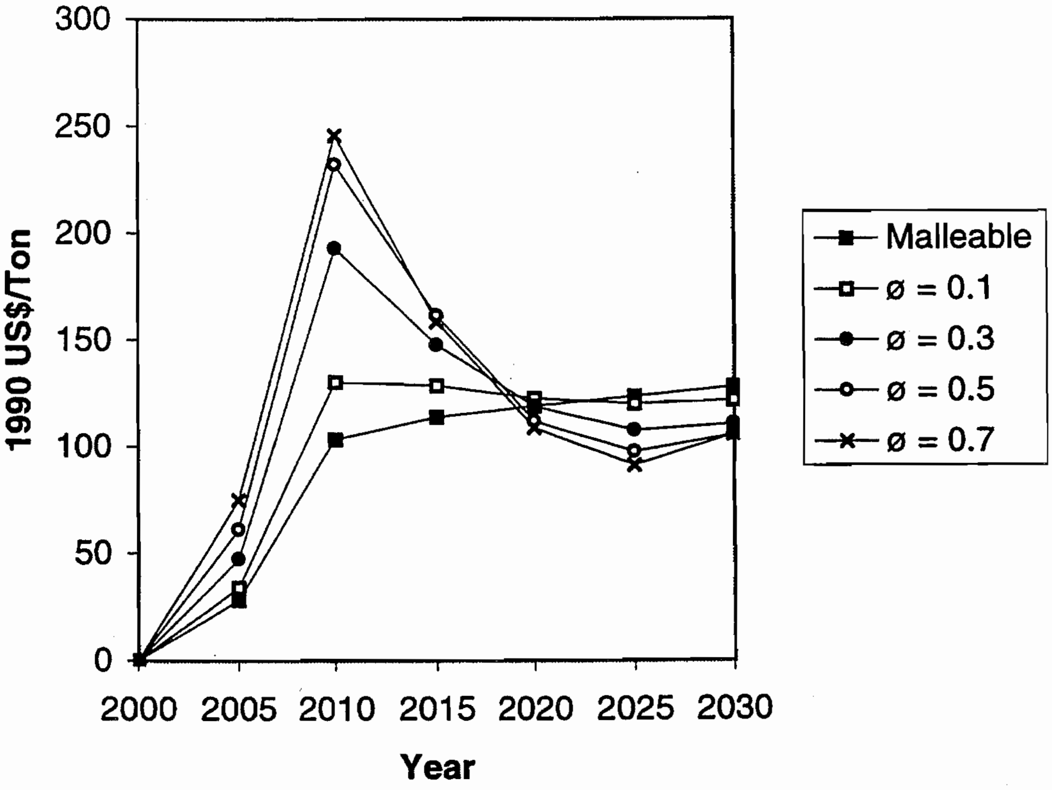


EFFECTS OF MALLEABILITY ON POLICY COST

To explore the implications of the Kyoto Protocol we make two simplifying assumptions. First, we assume that the Kyoto emissions targets are maintained unchanged throughout the analysis period to 2030, and that no additional nations join Annex I and undertake similar commitments. Second, we consider fossil CO_2 only. As shown by Reilly et al., (1999), ignoring the possible influence of carbon sinks and the non-CO_2 greenhouse gases leads to an overstatement of the required 2010 carbon price for the USA by a little over one-quarter, so their inclusion would not change the insights sought here.

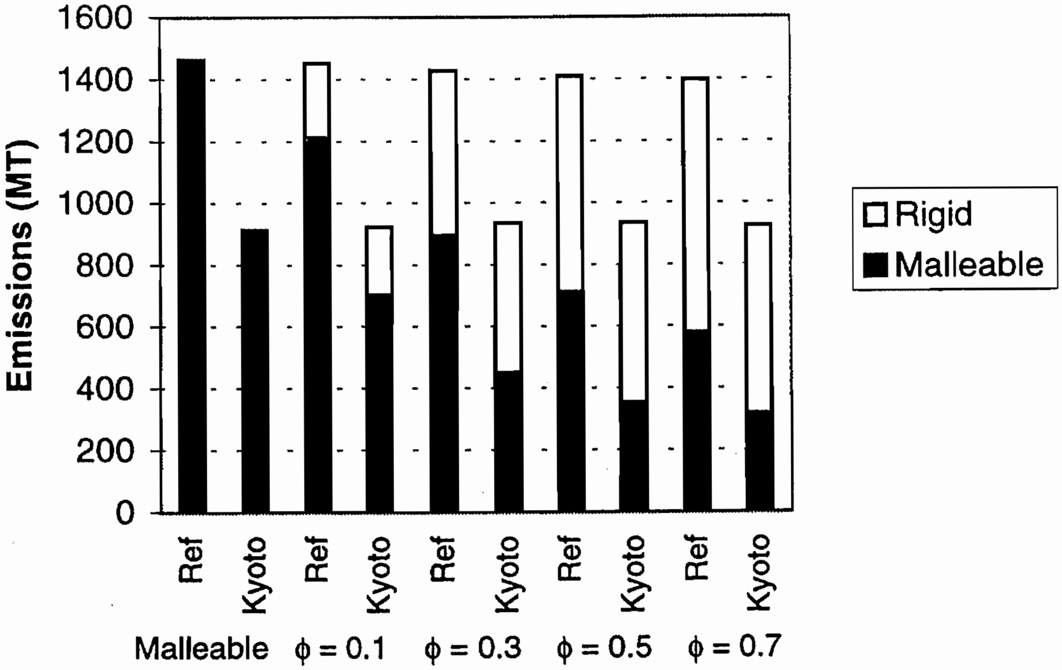
In the next section we consider the effects of a credible commitment to meet the Kyoto target coming at different times, but at this point we assume that the action is taken beginning in the year 2000. The resulting carbon prices for the USA are shown in Figure 4 for alternative values of the capital rigidity parameter, ϕ. A tightening carbon constraint reduces the total permissible carbon content of the aggregate fuel supply, prompting first inter-fuel substitution toward low-carbon fossil energy sources (*e.g.*, natural gas) and then actual reductions in the aggregate energy supply from fossil fuels. If the fuel and energy demand coefficients of the aggregate capital stock could be adjusted completely in each period to such a constraint, then the short-run cost of adapting to the carbon policy would be minimized. In 2010 the required price is around \$103 per ton of carbon (\$/tC) for $\phi = 0$, whereas at the other end of the range of ϕ values considered here the carbon price rises to as high as \$245/tC. All carbon prices are shown in 1990 U.S. dollars.

Figure 4. USA Carbon Price: Graduated Kyoto Constraint Beginning in 2000



The process underlying these changes can be seen in Figure 5. The Reference and Kyoto cases are presented, and the bars show the split of emissions between activities related to malleable capital and those tied to fixed capital. At the far left is the putty-putty case where there is no fixed capital. In part the Kyoto target is met by adjustments in the input proportions of the capital stock. At larger values of ϕ (i.e., less opportunity for retrofit) larger and larger quantities of emissions are coming from activities tied to the rigid portion of the capital stock, which necessitates ever more strenuous (and expensive) cuts in emissions from production activities in the malleable portion.

Figure 5.
USA Emissions by Type of Capital in 2010: Restrictions Beginning in 2000



Note also in Figure 4 that when capital is highly malleable ($\phi = 0$) the required carbon price rises monotonically over time, as the fixed constraint binds more tightly on the more rapidly growing USA economy. If capital is more rigid, however, the pattern is very different. The carbon price is at its highest in 2010, and then *falls* for some period of time. Such "overshooting" behavior comes about because the aggregate production structure can only undergo limited adjustment in the near-term, requiring a higher implicit carbon price to clear the market for emissions reductions and achieve the necessary changes in the input demand coefficients of the malleable portion of the capital stock. With more time, however, the older and least energy-efficient vintages of capital depreciate completely, and the input demand characteristics of aggregate capital gradually shift to factor proportions more appropriate to the new conditions. With the carbon constraint remaining at the Kyoto level the carbon price declines for a few periods, until economic growth ultimately forces it to resume an upward trend. By such time, however, the carbon price in the more rigid economy has been outstripped by that in the more malleable economy, due to the latter's faster growth of output and emissions.

In the analysis to follow, we adopt a reference value for the capital rigidity parameter of $\phi = 0.3$. This level is not intended as a "best" estimate, which awaits more analysis of the phenomenon, but is chosen to facilitate comparison with the results of other MIT studies of the Kyoto Protocol. Figure 4 shows that this assumption would lead to a carbon price in 2010 of around $193/tC. Assuming a single value of ϕ simplifies the presentation of results, so the fundamental insight can be drawn from the analysis.[8] However, it is worth re-emphasizing that the uncertainty surrounding the actual value of this parameter remains considerable, awaiting research on the process of capital turnover and empirical investigation of the influence of retrofit.

EFFECT OF THE TIME OF RATIFICATION

We have specified the point of credible commitment and start of emissions control action as the time when the Protocol goes into force. It seems plausible to assume that action by the U.S. Senate will be the key determinant of that date. The question is, when might this moment come? In October 1997, President Clinton laid out the timing of U.S. policy development on this issue. He initiated a Climate Change Technology Initiative (CCTI) which was intended to support increased R&D and to subsidize the introduction of low-emission technologies that are now available. A cap-and-trading system that could actually lower national emissions substantially was to be taken up after "a decade of experience, a decade of data, a decade of technical innovation" (The White House, 1997). The timing of subsequent steps could change, of course, in response to political events, such as a substantial revision of public attitudes about the climate issue. For the present, however, it appears unlikely that political conditions will be favorable to submission of the Protocol to the U.S. Senate for ratification until at least some time after the year 2000, if at all. If this happens, the prospects for actual ratification are even harder to forecast, although a Senate resolution stating necessary conditions for approval (U.S. Senate, 1997) and the tone of subsequent Senate hearings on this issue do not bode well for early ratification. Additionally, efforts by the Congress to block what some members have viewed as Administration efforts at "implementation without ratification" further dampens the expectation that, beyond the CCTI, there will be much activity in the United States until the ratification barrier is surmounted.

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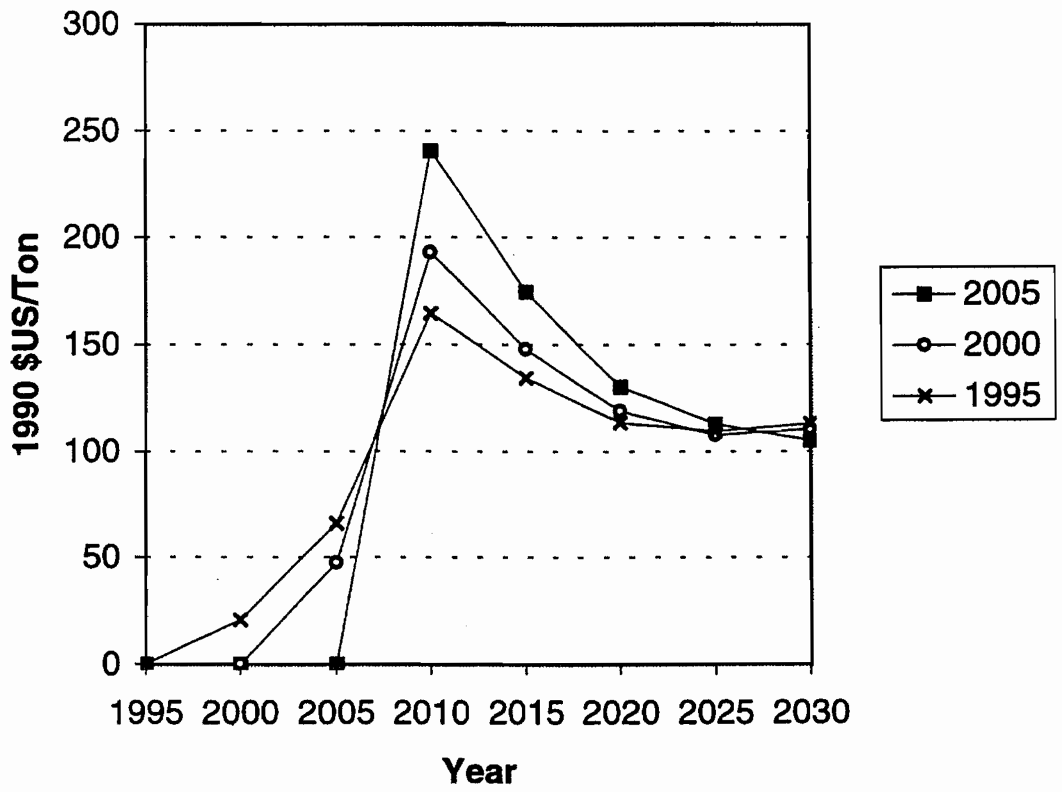
[8] The EPPA-derived carbon prices shown in the introductory chapter to this volume assume that reductions are initiated in the year 2000 and that $\phi = 0.3$.

To illustrate the implications of different degrees of lead time, we consider three different times of ratification. Our main focus is on analysis of the price of carbon for each period in the modeling horizon, which we take as indicative of the degree of short-term dislocation that the economy is likely to suffer and thus the feasibility of achieving the reductions required by Kyoto. Also, we examine the timing of ratification as it influences the net present value of a Kyoto achievement, viewed from 1990.

As shown in Figure 3, action to shift the emissions trajectory from the reference to the policy path begins at some ratification time *T*, which in this analysis is 5, 10, and 15 years ahead of the 2010 target date. Figure 4 showed the resulting carbon prices for $T = 2000$ and a range of values of ϕ. The required $193 carbon price under this condition and the carbon price for $\phi = 0.3$ is repeated in Figure 6, along with results for the other start times. Although it is now too late, it is interesting to compute how much easier the task would have been had a commitment to controls been agreed five years earlier. Just this small shift backward in time lowers the estimated 2010 carbon price from $193 to around $164/tC. What seems more likely, however, is that the time of ratification will come, if at all, not before 2005. The carbon price rises to $241/tC in this event.

Figure 6. USA Carbon Price: Effect of Abatement Start Date ($\phi = 0.3$)



Present value analysis of the welfare cost of the Kyoto commitment indicates that, for the United States, only for discount rates above 8% real is it better to wait until 2005 to initiate action. On the other hand, it is only for discount rates as low as 1% that a 1995 start would have been preferable, rather than waiting until 2000. These results are valid only for the assumed paths of reductions leading to the Kyoto target. In line with our focus, we did not determine the optimal pattern of policy restraint. The choice of different reduction paths may therefore shift these break points.

It should be noted that the shorter the time period (2010 - *T*) the less dependable is the estimate from a CES model like EPPA. The present analysis cannot model the influence of barriers that would affect the costs of adjustment in periods as short as five years, such as regulatory lags, design and equipment order times, and capacity constraints in supplier industries. In effect, if action does not come until only a few years before the budget period, then price shocks and related disruptions are implied that are outside the domain of CGE-type models, leading to an underestimate of the likely economic disruption. With this caveat in mind, however, an important message can still be drawn from the results shown in Figure 6. The longer the delay in initiating action the higher the carbon price needed to bring about the desired reduction as the time-frame grows shorter, until at some point in the span of years shown the Annex I commitments under the Kyoto Protocol are no longer credible, even as notional targets.

Savings from Emissions Trading in Annex I

The required carbon price could be reduced if carbon emissions trading among Annex I countries were arranged in time to influence the distribution of emissions reductions in 2010. The results in Table 3 show the substantial reduction in price of emissions permits that would be possible if the full gains of a system of Annex I trading could be realized. For $\phi = 0.3$ and ratification in 2000, for example, the carbon price would fall from $193 to $76/tC for the United States. For Japan and Europe, where EPPA estimates 2010 carbon prices (with no trading) to be substantially higher than the United States, the gain would be greater. Note that nations comprising the Former Soviet Union are below their Kyoto target in 2010, the gap representing some 330 MtC of "hot air" in these calculations.[9]

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[9] The carbon prices in the trading case are lower than results from earlier versions of the EPPA model (e.g., Jacoby, et al., 1997; Ellerman, Jacoby and Decaux, 1998). The difference arises from larger amounts of "hot air" in FSU, which of course is a highly uncertain quantity. The increased hot air results from updated assumptions about post-transition economic recovery and the rate of phase-out of fuel subsidies (particularly for coal) in FSU and EET.

Table 3. Carbon Prices in 2010, with and without Annex I Emissions Trading, for Alternative Times of Policy Initiation, $\phi=0.3$, (1990 US\$/tC)

	Date of Ratification/Action					
	1995		**2000**		**2005**	
	No trade	With trade	No trade	With trade	No trade	With trade
USA	165	71	193	76	241	89
JPN	453	↓	501	↓	591	↓
EEC	240		276		315	
OOE	230		247		283	
EET	66		71		82	
FSU	0		0		0	

The issue of timing of action should be stressed again with regard to a trading regime. Many years would be required to establish a full trading system, even after agreement was reached on its form under the Climate Convention. Thus the later the time of ratification *T* the less likely that any substantial portion of the savings shown in Table 3 would actually be realized during the 2008-2012 commitment period.[10]

CONCLUSIONS

The prices of carbon and associated energy services that would be required to achieve the Kyoto emissions targets are highly uncertain. Part of this uncertainty results from our limited knowledge of how easily the economy can respond to policy restraint over a period as short as five to ten years, and part originates in current doubt as to when action might actually be initiated.

The calculations above explore a key aspect of the likely response of the first component of this uncertainty, which is the speed with which the capital

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[10] The pattern of cost savings on the assumption that trading spreads gradually over time is explored by Ellerman, Jacoby and Decaux (1998) for a global trading case.

stock can be modified given the pace of depreciation and replacement, and the scope of opportunities for retrofit. Over periods of adjustment as short as the years between 1999 and the start of the first Kyoto commitment period, the required carbon price turns out to be very sensitive to this issue of malleability. We have concentrated on results for the USA, but the same pattern emerges for other Annex I regions. The processes of capital adjustment that are involved are poorly understood, which makes them an important topic for future research. Unfortunately, it does not appear that these uncertainties can be resolved in time to be relevant to policy choice regarding the Kyoto target. As a result, fulfilling the Kyoto commitment will require Annex I countries to take actions that involve a wide range of possible costs, which are not well represented either by the point estimates of single-scenario analyses or by the narrow sensitivity bands of this study. Domestic carbon policies will therefore have to be formulated in a world where it is impossible to know *ex ante* what commitment to a particular fixed target will cost.

Trading in emission allowances could lower the costs substantially, particularly for Europe and Japan. It is highly uncertain, however, how many years it might take to set up such a system, even after global agreement on its rules, or how much of the potential advantage might be gained as soon as the 2008-2012 period. Put another way, at present we cannot now tell whether the emissions reductions induced by a particular intended carbon price (perhaps to be achieved under a cap and trading system) will over- or undershoot the Kyoto target.

With regard to the second component of current uncertainty our results are more definitive. With each passing year the difficulty of meeting any fixed quantitative target increases progressively. Moreover, plausible estimates of when the Protocol would go into effect leave such a small window of time before the first commitment period that achievement of the Kyoto targets will eventually pass out of reach. Sooner or later, it seems to us, the Kyoto targets will need to be reconsidered. On the assumption that the targets-and-timetables approach to negotiations will prove a permanent feature of the Climate Convention (Jacoby, Schmalensee and Sue Wing, 1998), it will be important for any revision of Kyoto to consider how subsequent Protocols might be better constructed, given the uncertainties highlighted here.

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