

**PREM DISCUSSION PAPER SERIES:  
The Economics of Climate Change**

No. 1

August 2008

**A Tax-Based Approach to  
Slowing Global Climate Change**

Joseph E. Aldy  
Eduardo Ley  
Ian Parry





**World Bank**  
**Poverty Reduction and Economic Management Network**  
*The Economics of Climate Change*  
*Discussion Papers Series*  
**No. 1**

**A Tax-Based Approach to Slowing Global Climate Change**

**Joseph E. Aldy**

*Resources for the Future, Washington DC*

**Eduardo Ley**

*The World Bank, Washington DC*

**Ian Parry**

*Resources for the Future, Washington DC*

**August 2008**



**THE WORLD BANK**  
**Washington, D.C.**



CONTENTS

**FOREWORD** ..... **IV**

**ABSTRACT** ..... **V**

**ACKNOWLEDGEMENTS** ..... **VI**

**ABBREVIATIONS AND ACRONYMS**..... **VII**

**I. INTRODUCTION**..... **1**

**II. ISSUES IN THE CHOICE OF CONTROL INSTRUMENT—A DOMESTIC PERSPECTIVE**..... **2**

    A. COST-EFFECTIVENESS..... 3

    B. IMPLICATIONS OF ABATEMENT-COST UNCERTAINTY ..... 4

    C. COST-EFFECTIVENESS ACCOUNTING FOR FISCAL INTERACTIONS ..... 7

    D. DISTRIBUTIONAL CONSIDERATIONS..... 8

*Distributional Impacts Across Household Income Groups*..... 9

*Distributional Impacts on Energy-Intensive Firms*..... 9

    E. SUMMARY ..... 10

**III. DESIGNING A DOMESTIC CO<sub>2</sub> TAX**..... **11**

    A. TAX LEVEL ..... 11

    B. FURTHER DESIGN ISSUES ..... 13

*Point of Regulation* ..... 13

*International Emissions Leakage and Competitiveness* ..... 14

*Non-CO<sub>2</sub> GHGs*..... 15

*Incentives for Downstream Sequestration*..... 15

*Complementary Policies to Promote Technological Innovation*..... 16

    C. SUMMARY ..... 17

**IV. CO<sub>2</sub> TAXES AT A GLOBAL LEVEL** ..... **17**

    A. COST-EFFECTIVENESS..... 17

    B. EQUITY ..... 18

    C. BROAD COUNTRY PARTICIPATION ..... 19

    D. REACHING AGREEMENT ON TAXES OR TARGETS ..... 19

    E. INSTITUTIONAL CAPABILITY IN DEVELOPING AND INDUSTRIALIZING NATIONS ..... 20

    F. VERIFICATION ..... 20

**V. CONCLUDING REMARKS** ..... **21**

**REFERENCES**..... **23**

## FOREWORD

Climate change is a scientific reality with profound economic consequences. Average surface temperatures have already risen 1.4°F since the start of the 20<sup>th</sup> century—and further significant changes are likely. There is scientific consensus that this phenomenon is related to human economic activity. Greenhouse gases—of which carbon dioxide is the most prominent—have increased significantly since the Industrial Revolution, and current carbon dioxide levels in the atmosphere are at their highest level ever, and continue to rise due to economic activity.

Climate change will produce significant impacts on many countries; unfortunately it is likely to have very harmful effects for a large share of the world's population. For instance, several studies confirm that Africa is one of the most vulnerable continents to climate variability and change because of multiple stresses and low adaptive capacity. Analogously, within countries—in Africa and elsewhere—the poor are most at risk, because of their lower capacity to adjust to climate variations and their larger exposure to multiple strains—i.e., health status, access to water, agricultural income and lack of resources to mitigate risks.

It is clear that climate change affects the World Bank's core mission of fighting poverty. Moreover, since this challenge is superimposed on existing vulnerabilities; the issue is not *whether* climate change should weigh in development policies, but rather, *how* it should be incorporated in development strategies.

The Poverty Reduction and Economic Management (PREM) Network of the World Bank has prepared a special series on the *Economics of Climate Change*, as part of our efforts to raise awareness of poverty, distributional, financial, and fiscal consequences for developing countries.

Our hope is to help inform the debate and to highlight the importance of the issue from an economic and poverty-related point of view. After all, the world will be unable to face the challenges of climate change successfully if the poor are left behind.

Danny Leipziger  
Vice President and Head of Network  
Poverty Reduction and Economic Management (PREM)

**ABSTRACT**

*This paper discusses the design of CO<sub>2</sub> taxes at the domestic and international level and the choice of taxes versus a cap-and-trade system. There is a strong case for taxes on uncertainty, fiscal, and distributional grounds, though this critically hinges on policy specifics and how revenues are used. The efficient near-term tax is at least U.S. \$5–\$20 per ton of CO<sub>2</sub> and the tax should be imposed upstream with incentives for downstream sequestration and abatement of other greenhouse gases. At the international level a key challenge is the possibility that emissions taxes might be undermined through offsetting changes in other energy policies.*

**Key words:** Global climate change; CO<sub>2</sub> tax; cap-and-trade; policy design.

**JEL codes:** Q54; Q58; H23.

### **ACKNOWLEDGEMENTS**

We thank Richard Bird, Antonio Estache, Kirk Hamilton, John Horowitz, Danny Leipziger, Tim Irwin, Jon Strand, and George R. Zodrow for very helpful comments. The views expressed in this paper are the authors', and do not necessarily reflect those of the World Bank or its executive directors.

This paper is summarized in PREM Note Special Series on the Economics of Climate Change, No. 2, July 2008, "What is the Role of Carbon Taxes in Climate Change Mitigation?" available at <http://go.worldbank.org/8IVZXJXAW0>.

## ABBREVIATIONS AND ACRONYMS

BTU	British thermal unit
CO <sub>2</sub>	carbon dioxide
ETS	Emission Trading Scheme
EU	European Union
GDP	gross domestic product
GHGs	greenhouse gases
IPCC	Intergovernmental Panel on Climate Change
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
ppm	parts per million
R&D	research and development
VAT	value-added tax



*The U.S. must engage in an energy efficiency program that takes effect without delay and has meaningful bite. As long as developing countries can point to the U.S. as a free rider there will not be serious dialogue about what they are willing to do. I prefer carbon and/or gasoline tax measures to permit systems or heavy regulatory approaches because the latter are more likely to be economically inefficient and to be regressive.*

—**Lawrence Summers**, former U.S. Treasury Secretary, currently Professor at Harvard University (from “Practical Steps to Climate Control,” *The Financial Times* May 28, 2007).

*Frankly, a Kyoto-type framework—one with global quantitative emissions targets allocated among countries ... is not feasible. The only approach that will fulfill the conditions and relieve countries’ apprehensions regarding sovereignty and free riding is one in which all countries agree to penalize their carbon emissions in such a way that, over time, an internationally harmonized carbon price prevails. Consequently, the negotiation’s focus would not be on emissions quotas but on the harmonized carbon-price trajectory.*

*Of course, carbon taxes (on burning fossil fuels) would provide the easiest way for countries to comply with the system, and each country could then decide what to do with the tax revenue. Some might make their carbon tax revenue-neutral by reducing other taxes. The regime would allow countries (or associations of countries such as the EU) to comply with the internationally agreed-upon carbon price by means of their own national cap-and-trade systems. It would also let poor countries move toward the agreed trajectory of carbon prices more slowly than rich countries.*

*If you’re worried about climate change but don’t like carbon taxes, think about the messy or even impossible alternatives!*

—**Ernesto Zedillo**, former president of Mexico, currently Director of the Center for the Study of Globalization at Yale University (from “Carbon Prices, Not Quotas,” *Forbes* March 24, 2008).

## I. INTRODUCTION

There is widespread agreement on the desirability of a globally based effort to mitigate emissions of greenhouse gases (GHGs), particularly the primary gas, carbon dioxide (CO<sub>2</sub>), with the ultimate objective of stabilizing atmospheric GHG concentrations.<sup>1</sup> Of course, there is much dispute on how rapidly to scale back global CO<sub>2</sub> emissions. For practical policy purposes, however, the immediate issue is how to develop an international climate policy regime with a robust emission mitigation effort as its centerpiece, one that could incorporate rapidly industrializing nations over time, and that can adjust over time as more is learned about the science, economics, and technological change that characterizes the climate change problem.

For mitigating GHG emissions, economists favor emission taxes and cap-and-trade systems. Most of the policy discussion has focused on cap-and-trade systems, with the introduction of the European Union’s Emission Trading Scheme (ETS), and the emphasis on trading in most climate bills currently pending in the U.S. Congress. However, as the quotes by Secretary Summers and President Zedillo suggest, and we argue below, there is a potentially strong case for carbon taxes.

---

<sup>1</sup> The Intergovernmental Panel on Climate Change (2007) concludes that warming of the Earth’s climate system is unequivocal and that a delay in reducing GHGs significantly constrains opportunities to achieve lower climate stabilization targets. The U.S. National Academy of Sciences (2008) report states that “There is a growing concern about global warming and the impact it will have on people and the ecosystems on which they depend. [...] Temperatures will likely rise at least another 2°F (1.1°C), and possibly more than 11°F (6.1°C), over the next 100 years. This warming will cause significant changes in sea level, ecosystems, and ice cover, among other impacts.”

The policy landscape is not void of carbon taxes, as evident by the use of such taxes in northern Europe since the early 1990s, the recently implemented carbon tax in the Canadian province of British Columbia, and a couple of bills in the U.S. House of Representatives. And even if additional governments do not implement CO<sub>2</sub> taxes in the near term, it is important to assess the possible case for transitioning to a tax-based system over the longer haul. Thus, it is critical to understand how to design a CO<sub>2</sub> tax at a domestic and international level, and compare its advantages and disadvantages with a cap-and-trade approach. Since—in the political discourse—cap-and-trade is often heralded as a market-based approach, it is worth noting at the outset that both systems are equally market-based, in the sense that their effectiveness relies in affecting market behavior through emissions pricing.

This paper begins by comparing CO<sub>2</sub> taxes and emissions trading from a domestic perspective across a broad range of criteria of potential concern to policy makers.<sup>2</sup> Next we briefly discuss some further issues in the practical design of a domestic CO<sub>2</sub> tax. Following that we turn to issues in implementing CO<sub>2</sub> taxes at the global level. We then offer some concluding remarks.

## **II. ISSUES IN THE CHOICE OF CONTROL INSTRUMENT—A DOMESTIC PERSPECTIVE**

In choosing among control instruments, there is a wide array of criteria of potential concern to policy makers. These include cost-effectiveness, the ability to deal with uncertainty over emission abatement costs, and the incidence of the emission mitigation policy, particularly the distribution of costs borne by different household income groups and by industries. We discuss the appropriate stringency of domestic climate policy later.

Even evaluating policies on a single criterion alone can be tricky. For example, the overall cost and distributional impacts of CO<sub>2</sub> taxes depend critically on what the government does with the revenues collected from those taxes. Further, satisfying one criterion may limit the government's ability to address another criterion. For instance, using some CO<sub>2</sub> tax revenues to provide compensation to politically influential groups may raise the overall costs of the policy, by reducing revenues that might otherwise have been available for cutting other taxes that distort economic activity. Finally, comparing CO<sub>2</sub> taxes and cap-and-trade systems in their "pure" form does not do justice to the full spectrum of policy options. Policy makers may modify either instrument's design, at least to some extent, to exploit apparent advantages of the other instrument.

This section takes each of the major criteria in turn and discusses to what extent, if any, they imply a strong case for preferring CO<sub>2</sub> taxes to other emissions mitigation instruments, primarily cap-and-trade systems.<sup>3</sup>

---

<sup>2</sup> We focus on CO<sub>2</sub> taxes for ease of exposition. As discussed below, climate change policy should also target various other non-CO<sub>2</sub> GHGs. Most of the discussion here is from the perspective of a prototypical developed country; we touch only briefly on issues related to implementation and monitoring that may be relevant for less developed countries.

<sup>3</sup> Goulder and Parry (2008), Aldy et al. (2008), and Hepburn (2006) also provide broad discussions of the literature on alternative emissions control instruments. Our discussion in this section draws most heavily from Goulder and Parry (2008).

## A. Cost-Effectiveness

We start with cost-effectiveness, using the more traditional and narrow definition of cost that encompasses only changes in economic efficiency in the markets directly affected by the emission mitigation policy. This notion of cost essentially reflects the loss of benefits to fossil fuel users, minus savings in production costs from reduced fossil fuel supply. Under this narrow definition, emissions taxes and cap-and-trade systems can essentially be viewed as equivalent instruments. This equivalency breaks down, however, when we account for abatement-cost uncertainty (section II.B), and for how policies interact with the broader fiscal system (section II.C).

In the context of the narrow definition, cost minimization requires equating marginal abatement costs across all emission sources. These options include:

1. Switching to fuels with lower, or zero, carbon content. In the power sector, for example, this would involve substituting coal-fired generation with generation from natural gas, nuclear, hydro-, wind, and solar power.
2. Adoption of energy-conserving technologies to lower fuel requirements per unit of economic activity. In the transportation sector, for example, this would include incorporation of technologies to improve vehicle fuel economy. In the residential sector, it would include upgrading the efficiency of lighting, heating, and cooling systems as well as adoption of more energy-efficient appliances.
3. Reducing overall demand for energy-intensive activities, for example, traveling less or dwelling in smaller homes.
4. Sequestering carbon to partly offset emissions, through carbon capture and storage technologies at coal plants or other industrial facilities, and expanding forested land or modifying agricultural techniques to sequester carbon in soil.

In principle, when all firms and households face a common price per unit of CO<sub>2</sub> embodied in fuels and energy-intensive products, then no additional policies can lower the total cost of attaining a specified policy goal. These cost-minimizing conditions could be largely achieved under a CO<sub>2</sub> tax applied upstream in the fossil fuel supply chain, with corresponding tax credits for downstream sequestration. This tax, which would be levied in proportion to a fuel's carbon content, would be largely passed forward into the price of coal, natural gas, and petroleum products, and therefore ultimately embodied into the price of electricity and other energy-intensive products. This *carbon added tax* system, along the "carbon chain," would work much in the same way as a typical value added tax (VAT) under the standard credit-invoice system, along the value chain.<sup>4</sup>

---

<sup>4</sup> The carbon taxes dating to the early 1990s in Denmark, Finland, Norway, and Sweden do not achieve cost-effective emission mitigation because they allow for significant variation in the tax per unit of carbon by fuels and by sectors (Bruvoll and Larsen, 2004; Vehmas, 2005). In contrast, the British Columbia CO<sub>2</sub> tax imposes a uniform rate on carbon across different fossil fuels (Government of British Columbia, 2008).

The same efficiency conditions could also be met under an upstream cap-and-trade system, where firms require allowances to cover the carbon content of fuels they mine or process—with the market price of allowances established in permit trading markets. This price is then passed forward into fuel prices. With competitive markets, and appropriate crediting provisions for downstream sequestration, there is very little difference between emission taxes and cap-and-trade systems, in terms of the emission mitigation that they encourage.<sup>5</sup>

Direct regulatory instruments, like mandates to install specific emissions control or energy-saving technologies, or requirements on the performance of firm production, fail to meet the cost-minimizing criterion. Compared with a CO<sub>2</sub> tax or cap-and-trade system, and for the same economy-wide emission goal, some abatement opportunities are over-burdened under direct regulation, while others are under-exploited or not exploited at all.<sup>6</sup>

### **B. Implications of Abatement-Cost Uncertainty**

Uncertainty over the future costs of emissions abatement is inevitable as costs will vary with fuel prices, the strength of domestic energy demand, unpredictable advances in energy-saving technologies, and so forth. Abatement costs, however, will also depend on the choice of emissions control instrument. CO<sub>2</sub> taxes fix the price of emissions, and therefore the marginal costs of abatement, while allowing the quantity of emissions to vary with economic conditions. In contrast, a pure cap-and-trade system fixes the quantity of emissions, leaving marginal abatement costs to fluctuate with economic conditions.

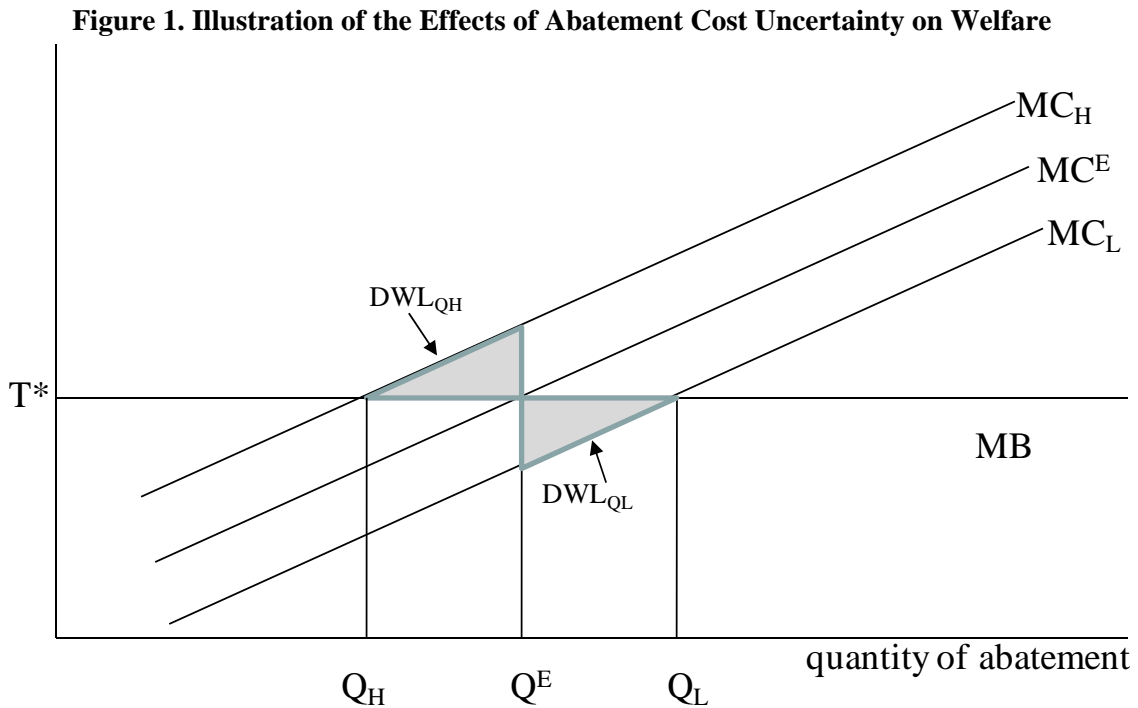
From the perspective of maximizing expected economic welfare, CO<sub>2</sub> taxes have an advantage over cap-and-trade systems. CO<sub>2</sub> taxes and cap-and-trade systems both affect the flow of emissions, although it is the atmospheric stock of gases that drive climate change damages. The stock changes slowly, because of the long atmospheric residence of CO<sub>2</sub> (on average about a hundred years). For example, the Mauna Loa record dating to 1959 shows that atmospheric CO<sub>2</sub> concentrations grow about 1 to 2 parts per million (ppm) annually, on a pre-industrial base of about 270 ppm. Since global emissions in any given year have a proportionately small impact on the stock of CO<sub>2</sub>, the marginal benefits of abatement are essentially perfectly elastic.

---

<sup>5</sup> In practice, achieving cost-effectiveness may be more difficult under cap-and-trade in the early years, due to additional informational requirements. Under a tax, the future emissions price is known, while under cap-and-trade firms must project future allowance prices. To the extent that price expectations among firms differ, this may lead to a disparity in marginal abatement costs across emissions-reducing capital investments. Whether this significantly compromises the cost-effectiveness of emissions trading schemes has not been explored in the literature.

<sup>6</sup> Consider, for example, standards for the average fuel economy of vehicles in a manufacturer's sales fleet. By itself, of course, this policy fails to exploit any emission mitigation opportunities outside of the automobile sector. This substantially reduces the cost-effectiveness of the policy (relative to an economy-wide CO<sub>2</sub> tax) given that, in the United States for example, automobiles only account for one-fifth of nationwide CO<sub>2</sub> emissions (Energy Information Administration, 2008). Nor does the policy encourage any downstream sequestration activities. Even within the automobile sector, the policy does not exploit emission mitigation through reduced vehicle miles of travel because, unlike a gasoline tax, or a tax on the carbon content of gasoline, fuel economy regulations do not increase fuel costs per mile driven. Furthermore, unless fuel economy credits are tradable across firms, there is no automatic mechanism for equating the marginal costs of improving fuel economy across different auto manufacturers. Austin and Dinan (2005) find that the long-run costs of reducing gasoline or, equivalently, CO<sub>2</sub> emissions, from automobiles, by around 10 percent, would be about 70 percent greater under tighter fuel economy regulations than under higher gasoline taxes.

Figure 1 illustrates the potential welfare effects of ex ante efficient policies in this setting (based on Weitzman, 1974).  $MC^E$  is the expected marginal cost schedule for emissions abatement, while  $MB$  is the marginal benefit from abatement. If marginal costs turn out to be higher than anticipated,  $MC_H$ , then the efficient amount of abatement is  $Q_H$ , while if costs are lower than expected,  $MC_L$ , optimal abatement is  $Q_L$ . A Pigouvian emissions tax of  $T^*$ , equal to marginal benefits, automatically generates these efficient abatement levels, regardless of the position of the marginal cost curve. In contrast, under a fixed emissions cap of  $Q^E$ , abatement will be excessive if marginal costs are higher than expected, or too low if marginal costs are lower than expected, resulting in deadweight losses, relative to the emissions tax, shown by the shaded triangles in Figure 1. In fact the welfare differences between carbon emissions taxes and cap-and-trade systems can be striking. For example, simulations in Pizer (2002) and Newell and Pizer (2003) find that a  $CO_2$  tax could result in welfare gains up to five times those of the expectation-equivalent cap-and-trade system.<sup>7</sup>



Alternatively, if the policy maker aims to minimize the present discounted value of costs for limiting emissions released into the atmosphere over a long period of time, then emission taxes again have the advantage over cap-and-trade. An emissions tax rising at the rate of interest over time (net of the “depreciation rate” of atmospheric accumulations of emissions) will equate the present value of marginal abatement costs across different periods. In contrast, under a pure allowance system, abatement will be excessive (and allowance prices too high) in periods when

<sup>7</sup> Uncertainty over the marginal benefits from abatement does not affect these results, so long as this is independent of uncertainty over marginal abatement costs (Stavins, 1996). This is a reasonable approximation for the near term.

meeting the fixed cap is more costly than average, while abatement will be too low in other periods when the marginal costs of meeting the cap are lower than average.

However, modifying a cap-and-trade system to incorporate some of the price-stabilizing characteristics of an emission tax can mitigate some of the welfare differences between pure forms of these two instruments. For example, a hybrid tax-allowance approach, often referred to as a safety valve, could reduce price volatility (Kopp et al., 1997; McKibbin and Wilcoxon, 1997; Jacoby and Ellerman, 2004). The government would agree to sell an unlimited number of additional allowances at a predetermined price into a cap-and-trade market. If emission trading results in allowance prices below this predetermined price, then the market behaves as a normal cap-and-trade regime. The safety valve serves as a ceiling on the allowance price, and if prices increase enough that it becomes economic for firms to tap this provision instead of buying allowances at even higher prices, then the system effectively transforms into a tax: firms purchase safety valve allowances thereby relaxing the cap on the program's emissions.

In a related policy context, the safety valve has already become a part of implementing renewable energy goals. The Massachusetts renewable portfolio standard for its power sector allows utilities to buy and sell renewable energy credits. In lieu of holding sufficient credits to satisfy the standard, utilities may also comply with their regulatory obligation by making Alternative Compliance Payments, initially set at \$50 per megawatt-hour in 2003 and adjusted annually for inflation (Massachusetts Division of Energy Resources, 2008).<sup>8</sup>

The basic model of cap-and-trade allows for firms to equate marginal costs of abatement across all sources. Modifying cap-and-trade to allow intertemporal emission trading would provide the opportunity to firms to equate (discounted) marginal costs over time and facilitate efforts to smooth out year-to-year allowance price volatility. Unfettered intertemporal trading would allow firms to bank allowances for use later—for example, when current prices are low and expected future prices are high—and to borrow allowances from future periods when future prices are expected to be lower than current prices.<sup>9</sup> The European ETS now allows full banking of emission allowances; however firms are not allowed to borrow allowances from future policy commitment periods. This could create problems in the near term (before firms have accumulated a substantial bank of allowances) as it leaves the system vulnerable to shocks, such as a jump in natural gas prices that would raise the costs of fuel switching in the power sector.<sup>10</sup>

A further alternative would be to attempt to stabilize the allowance market through a “Climate Fed” that could counteract severe price volatility through buying or selling allowances to the market in times of unusually high or low prices. Several U.S. domestic climate policy bills

---

<sup>8</sup> In this paper, all dollar amounts are U.S. unless noted otherwise.

<sup>9</sup> Borrowing could take two forms. First, the government may allocate multiple years' worth of permits at the beginning of the cap-and-trade system and firms would have the discretion when to use permits of various vintages. Second, firms could go to the government and borrow permits that would then translate into smaller future allocations.

<sup>10</sup> The banking provisions were introduced after the pilot phase of the ETS witnessed quite volatile allowance prices. But even with banking, CO<sub>2</sub> prices continue to fluctuate, with the maximum daily allowance price about 33 percent higher than the minimum price over the first three-and-a-half months of 2008 (allowance prices are posted at [www.pointcarbon.com](http://www.pointcarbon.com)). To the extent that this causes marginal abatement costs to vary substantially within a period of just a few months, the cost-effectiveness of the cap-and-trade system is significantly undermined.

envision this type of scheme. One could consider a variety of tools at the disposal of the Climate Fed, such as relaxing emission caps, reallocating caps by borrowing emissions from future periods to augment current period allowance allocations, or increasing the amount of offsets that would be allowed into the cap-and-trade regime.

### **C. Cost-Effectiveness Accounting for Fiscal Interactions**

The overall economic costs of emission mitigation policies, and the choice among different instruments, is further complicated by how these policies interact with distortions elsewhere in the economy created by the broader tax system.

The environmental tax literature emphasizes that emission taxes potentially impact tax distortions in economy-wide factor markets—particularly those in the labor market created by income and payroll taxes—in two main ways (for example, Goulder, 1995). First, using CO<sub>2</sub> tax revenues to reduce existing factor taxes generates a gain in economic efficiency, equal to the increase in labor (or capital) supply, times the wedge between the gross factor price and net-of-tax factor price.<sup>11</sup> The potential welfare gains, even from very small increases in the supply of capital and labor, could be relatively large because the benefits of tax rate reductions apply to the entire economy while the costs of abatement accrue primarily to the energy sector (for example, Parry et al., 1999).

However, there is an offsetting effect. As firms pass CO<sub>2</sub> taxes forward into higher energy prices, this drives up product prices in general, thereby depressing the real return to work effort and savings—that is, the amount of goods that people can buy with their take-home wages or income from savings. Reducing the buying power (real returns to) capital and labor depresses labor supply and capital accumulation. This so-called “tax-interaction effect” compounds the current tax distortions in factor markets and increases the costs of the climate policy.

A large literature on these two effects has evolved over the past 15 years, and most analyses find that the costly tax-interaction exceeds the beneficial revenue-recycling effect, implying that the overall costs of carbon taxes are somewhat larger than the costs of carbon reductions in fossil fuel and energy markets (for example, Bovenberg and Goulder, 2002). However the magnitude of the revenue-recycling effect is highly sensitive to the details of the tax shift. For example, if the CO<sub>2</sub> tax revenue is predominantly used to reduce taxes on capital income, the revenue-recycling effect is larger (as capital taxes are thought to involve higher distortionary costs at the margin than labor taxes) and could exceed the tax-interaction effect (Bovenberg and Goulder, 1997). Alternatively, if CO<sub>2</sub> tax revenue is used to cut marginal personal income tax rates this can also raise the revenue-recycling effect above the tax-interaction effect by (slightly) reducing distortions between ordinary spending and tax-favored spending home ownership, employer medical insurance, and so forth (Parry and Bento, 2000). On the other hand, using revenue to raise personal income tax thresholds, or introduce similar threshold exemptions for payroll taxes,

---

<sup>11</sup> The gross factor price reflects the marginal value of production to firms from the last unit of the factor, while the net factor price reflects the marginal cost of factor supply to households (for example, the marginal cost of foregone nonmarket time). This applies, at least, when factor markets are competitive. Factor market impacts are more opaque in the presence of institutional wage setting, which is important in certain European labor markets (Bosello et al., 2001).

would produce a smaller revenue-recycling benefit, as this encourages more labor force participation but not additional effort on the job or longer work hours.

In contrast to a (revenue-neutral) CO<sub>2</sub> tax, a cap-and-trade program with gratis allocation incurs much higher total costs. The government foregoes collecting revenues when it transfers free allowances to firms, but the allowance price yields the same tax-interaction effect—by increasing energy costs—as if an emission tax were imposed at the same price. The cost advantage of (revenue-neutral) emission taxes can be substantial. For example, a \$10 per ton CO<sub>2</sub> tax (\$37 per ton of carbon) could lower U.S. emissions by 5–10 percent and raise annual revenues of approximately \$60 billion in the near term. If the government used this revenue to reduce income taxes, based on typical assumptions in the literature, the CO<sub>2</sub> tax would deliver roughly \$20 billion per year in cost savings over an equivalent cap-and-trade system that did not exploit a similar revenue-recycling approach.<sup>12</sup>

Of course in practice, CO<sub>2</sub> revenues might be squandered in special interest spending, rather than used to cut other distortionary taxes (or finance other socially desirable public spending), thereby reducing, and possibly even reversing, the sign of the revenue-recycling benefit. Conversely, a cap-and-trade program could exploit the revenue-recycling effect if allowances were auctioned off by the government. Again therefore, whether there is a strong case for emissions taxes over cap-and-trade depends critically on the details of the accompanying legislation.

The plan for the European ETS is to transition to a fully auctioned allowance system by 2020 (CEC, 2008), incorporating into the system one of the key attractions of the emission tax alternative. It is not yet clear, however, how all this new revenue will be used, as the plan does not specify revenue-neutrality. In contrast, Sweden began using carbon tax revenue in 2000 to offset labor taxes (Government of Sweden, 2005). British Columbia implemented a CO<sub>2</sub> tax of \$10 per ton in July 2008, with a ramp-up of \$5 per ton CO<sub>2</sub> per year until reaching \$30 per ton in 2012. The BC carbon tax program stipulates revenue neutrality and the only permissible form of revenue recycling is the reduction of taxes borne by individuals and businesses (Government of British Columbia, 2008).<sup>13</sup>

#### **D. Distributional Considerations**

For reasons of fairness and practical feasibility, policy makers have expressed concern over the distributional burdens of domestic mitigation policies on different household income groups

---

<sup>12</sup> There are two caveats to this. First, even cap-and-trade systems with entirely free allowance allocation can raise a limited amount of revenue for the government indirectly (perhaps around 40 percent of that raised directly under the equivalent emissions tax). This occurs as firms receiving allowances with market value for free experience an increase in their equity values, which, in turn, leads to higher corporate taxes and ultimately higher income and capital gains taxes for individual shareholders. Second, the tax-interaction effect maybe somewhat weaker under freely allocated permits than under emissions taxes in countries (like the United States) that retain some price regulation in the power sector. Electric utilities subject to such regulation cannot pass through the market value of freely received permits into higher generation prices (Burtraw et al., 2002); in turn this weakens the policy's impact on the overall price level, and hence limits the reduction in real factor returns and the tax-interaction effect.

<sup>13</sup> The revenues from Norway's CO<sub>2</sub> tax go to general revenues so it is not clear whether this ultimately results in greater public spending or reduced rates for other taxes (Daugbjerg and Pedersen, 2004).

and on energy-intensive industries. Although pure emission taxes and cap-and-trade systems have very different distributional implications, again the government can modify either instrument to mimic, at least in part, any distributional advantage of the other instrument.

### *Distributional Impacts Across Household Income Groups*

Low-income households are more vulnerable to increases in the price of energy-intensive goods like electricity, home heating fuels, and gasoline, since they spend a larger share of their budget on these items compared with wealthier households. The regressivity of CO<sub>2</sub> taxes—reflected by lower income groups having a greater burden-to-income ratio than higher income groups—varies by the time frame of measurement. Generally, analysts prefer using a measure of lifetime income in incidence analysis, as this better reflects households' long-run consumption possibilities, though measuring lifetime income, presents difficult technical and data challenges. Studies that use a measure of lifetime, as opposed to annual, income find that CO<sub>2</sub> taxes are less regressive than static analyses suggest (see Parry et al., 2006 for a review).

Traditional cap-and-trade systems with free allowance allocation provide no mechanism for addressing concerns about the disproportionate burden of higher energy prices on lower-income households. In fact, they make the problem worse by widening the disparity in burden-to-income ratios among lower and higher income households. Giving away for free allowances with market value raises firm profits and equity values and this ultimately benefits shareholders, who tend to be concentrated in upper-income groups. In fact, for a cap-and-trade system with free allocation mitigating CO<sub>2</sub> emissions by 15 percent, Dinan and Rogers (2002) find that the program overcompensates the wealthiest households, as their additional capital income substantially exceeds the burden on them from higher energy prices.

In contrast under a CO<sub>2</sub> tax, or auctioned allowance system, policy makers can address fairness concerns, at least in part, through recycling some of the revenue in ways that disproportionately benefit low-income households, such as reductions in payroll taxes, or increases in income tax thresholds. For example, Metcalf (2007) outlines a scheme for a \$15 per ton tax on CO<sub>2</sub> emissions (\$55 per ton of carbon) in the United States, with revenues funding payroll tax rebates in a manner that imposes the same approximate burden-to-income ratio across income deciles. Some elderly or other nonworking households, however, do not benefit from payroll tax reductions and may require compensation through other means, such as targeted energy assistance programs. Recycling CO<sub>2</sub> tax revenues in ways that disproportionately help lower income households may involve some sacrifice of economic efficiency compared with across-the-board reductions in distortionary taxes, though the potential empirical magnitude of these losses has not received attention in the literature.

### *Distributional Impacts on Energy-Intensive Firms*

Some have advocated gratis allowance allocations to the business community to effectively secure their support for climate change policy (for example, McKibbin and Wilcoxon 2007). Clearly, providing some compensation for politically influential industries most affected by federal climate policy for their loss of equity value might be part of the political deal making needed to move legislation forward. To the extent that firms' (short run) supply curves slope

upward rather than being perfectly elastic, some of the burden of the emissions mitigation policy may come at the expense of lower producer surplus (through a reduction in producer prices) rather than the entire burden being passed forward in higher consumer prices.

Under a cap-and-trade system, the government can compensate firms by giving them an allowance allocation with a market value equal to their potential reduction in equity value or producer surplus. A domestic CO<sub>2</sub> cap-and-trade program with free allocation of 15–20 percent of total emission allowances could keep fuel suppliers and power generators whole (Bovenberg and Goulder, 2001; Smith, Ross and Montgomery, 2002).<sup>14</sup> Providing such compensation has a cost, as it reduces the amount of revenue that could potentially finance reductions in other distortionary taxes. For example, Bovenberg and Goulder (2001) estimate the overall costs of freely distributing 15–20 percent of allowances would be about 7 percent greater than a 100 percent auction to finance reductions in distortionary taxes. Obviously, the total cost increases much more under a more aggressive program to mitigate emissions that requires greater compensation.

The government could pursue a similar approach under a CO<sub>2</sub> tax by providing inframarginal exemptions. For example, the tax could apply only after a firm's emissions equal to 15–20 percent of historic emissions, allowing for full compensation just as if the firm had received 15–20 percent of emission allowances for free under a cap-and-trade program.<sup>15</sup>

In some cases, emissions sources have been exempt outright from CO<sub>2</sub> taxes. For example, Norway's CO<sub>2</sub> tax, implemented in 1991, covered about only two-thirds of the economy's emissions, while in 1993 a reform of Sweden's CO<sub>2</sub> tax exempted industrial sources from paying carbon taxes on electricity and fossil fuels. These exemptions obviously raise the overall costs of the CO<sub>2</sub> tax (relative to a comprehensive tax) by failing to exploit low-cost abatement opportunities in the exempt sector.

## E. Summary

The case for preferring CO<sub>2</sub> taxes to cap-and-trade systems depends critically on several design choices. If cap-and-trade programs incorporate provisions to contain allowance price volatility and to transition to full revenue-neutral allowance auctions, then a CO<sub>2</sub> tax may not strongly dominate a cap-and-trade regime. If the only politically viable type of cap-and-trade system is of the pure form, however, then CO<sub>2</sub> taxes are a far better alternative, so long as revenues are used judiciously, and large emissions sources are not exempt from the tax.

---

<sup>14</sup> Compensation would become more difficult (that is, require a greater share of allowances given away for free) as the emissions cap is progressively tightened over time, and beyond some point even giving away 100 percent of the allowances will not be sufficient to fully compensate firms. This issue might be addressed through excess compensation in the early years of the program (for example, Stavins, 2007). Progressively phasing out compensation over time makes sense because it avoids potential difficulties in updating the share of the allowance cap going to different firms, as different firms expand or contract at different rates in the future.

<sup>15</sup> Compensation for firms lying downstream of the point of regulation (for example, power companies) could also be provided under either policy, through free allowance distribution, or temporary relief from other taxes.

### III. DESIGNING A DOMESTIC CO<sub>2</sub> TAX

We now discuss further practical issues in the design of a domestic CO<sub>2</sub> tax: setting the emission price (tax level); choosing the point of regulation; addressing emission leakage from industrial relocation; incorporating non-CO<sub>2</sub> GHGs and downstream sequestration activities; and identifying complementary technology policies.<sup>16</sup>

#### A. Tax Level

Standard economic welfare-maximizing theory recommends that the appropriate CO<sub>2</sub> tax should reflect the world consequences from the estimated future climate change impacts per ton of current CO<sub>2</sub> emissions. These consequences encompass damages to agriculture, the impacts of (and costs of protecting against) rising sea levels and increased storm intensity, health effects (for example, from the possible spread of tropical disease), ecological disruptions, the risks of major disruptions to world output from more extreme climate scenarios, and so forth. Predicting and valuing these impacts is extremely difficult and controversial (for example, Mendelsohn, 2005).

For example, there is substantial uncertainty over the extent and timing of future global warming, as well as the accompanying climate changes that might be experienced at a regional level. Data available for quantifying the nonmarket impacts of climate change, such as migration of ecosystems, is very sparse. The appropriate discount rate for valuing the very long-term impacts of today's emissions is disputed.<sup>17</sup> And uncertainty over the pace of future economic growth and technological development makes it very difficult to project the vulnerability of the world to climate change occurring several decades or more from now. Most difficult of all is incorporating the risks of catastrophic climate change, such as some feedback effect or nonlinearity in the climate system leading to extreme warming scenarios.

Despite all these challenges, there is an evolving valuation literature that attempts, albeit very roughly, to put a price on CO<sub>2</sub> emissions under different future climate scenarios. Most estimates put the future damages from today's emissions at the equivalent of around \$5 to \$20 per ton of CO<sub>2</sub> (\$20 to \$75 per ton carbon) (Tol, 2007). The most comprehensive estimates, developed by Nordhaus and Boyer (2000), and updated in Nordhaus (2008), put the optimal (global) price at \$9.5 per ton of CO<sub>2</sub> in 2015, rising at about 2 to 2.5 percent per year to \$23 per ton by 2050 and \$56 per ton by 2100 (prices are in 2005 dollars).<sup>18</sup> Table 1 illustrates what this level of near-term CO<sub>2</sub> price would imply for certain energy and fuel prices.

---

<sup>16</sup> Kopp and Pizer (2007) and Stavins (2007) also provide broad discussions of the literature on designing emissions control instruments.

<sup>17</sup> Impacts are very long range, not only because emissions have a very long residence time in the atmosphere, but also because it takes decades for global temperatures to fully adjust to a change in atmospheric accumulations due to gradual heat diffusion processes in the oceans.

<sup>18</sup> Roughly speaking, the optimal tax rises at the rate of growth in world output potentially affected by future global warming. At first glance, it might be thought that the tax should increase at a faster rate, given that damages are convex in the extent of climate change. However, in Nordhaus and Boyer (2000), this effect is roughly offset, because warming is taken to be a concave function of the atmospheric concentration of GHGs.

**Table 1. Equivalency of Units**

<i>Tax of \$10 per ton of CO<sub>2</sub> equals:</i>	
\$36.7	Per ton of Carbon
\$4.77	Per barrel of oil
¢8.80	Per gallon of gasoline
¢2.29	Per liter of gasoline
¢0.78	Per kilowatt-hour of electricity

*Source:* [www.epa.gov/solar/energy-resources/calculator.html](http://www.epa.gov/solar/energy-resources/calculator.html).

*Note:* The CO<sub>2</sub> price can also be expressed per million BTU of fuel. For example, a \$10 CO<sub>2</sub> price amounts to \$1.08, \$1.06, \$1.03 for lignite, sub-bituminous, and bituminous coal respectively, and ¢87 for residential fuel oil, ¢82 for crude oil, ¢79 for gasoline, and ¢59 for natural gas, where all units are million BTU of fuel.

Some studies, however, suggest substantially higher near-term emissions prices. In particular, Stern (2007)'s central estimate of the current marginal damage per ton of CO<sub>2</sub> is around \$85. Stern (2007)'s estimates of the total damages from a given amount of warming (expressed as a percent of world GDP) are broadly similar to those in Nordhaus and Boyer (2000), although the relative contribution of market impacts, nonmarket effects, and catastrophic risks is strikingly different in the two studies. As discussed extensively in Nordhaus (2007), marginal damages are dramatically larger in Stern (2007) because disutility to future (unborn) generations is not discounted in the latter study, which greatly magnifies the present value of distant damages, especially when they become very large after 2100.<sup>19</sup>

Weitzman (2008) provides an alternative perspective on catastrophic damages.<sup>20</sup> He shows that, under a plausible utility function, we cannot put an upper bound on marginal damages when there is a positive, albeit a very small and very distant, probability of destroying the planet as we know it—in his case, this is the possibility of extreme warming reducing worldwide consumption by 99 percent indefinitely.<sup>21</sup> Analysts that are broadly sympathetic to this viewpoint tend to reject attempts to assess Pigouvian emissions taxes and instead focus on least-cost emissions pricing trajectories consistent with ultimately stabilizing atmospheric GHG concentrations at alternative target levels.

A number of modeling groups have projected such pricing paths, though we focus here on a study by Clarke et al. (2007), employing three widely respected energy-economic models, for the

<sup>19</sup> The appropriate rate at which to discount future global warming damages is extremely contentious—essentially it is a philosophical issue that is not going to be resolved any time soon. In our view, economists should objectively lay out the case for and against different assumptions, and what these imply for policy, and let the policy makers decide how to proceed. Low, or zero, discount rates might be appealing on ethical grounds, given that damages will affect people who have not been born yet. But applying these rates in other contexts leads to perverse implications, such as, for example, all previous (low-consumption) generations should have been made even worse off to make our (high-consumption) generation better off.

<sup>20</sup> In Nordhaus and Boyer (2000) and Stern (2007) catastrophic damages are quantified based on the subjective views of experts concerning the risks of losing, in perpetuity, a large portion (though not infinitely large portion) of world GDP, for different levels of warming.

<sup>21</sup> Weitzman (2008) also suggests that cost-benefit analysis is not a useful tool for guiding climate policy, when there is uncertainty surrounding both the variance and the mean temperature change (or its effects on economic activity). In this 'fat-tails' case, the outcome of cost-benefit analysis is highly sensitive to rather arbitrary modeling choices about things that we know little about, namely climate damage functions.

U.S. Climate Change Science Program. The models generated carbon price trajectories consistent with stabilizing atmospheric CO<sub>2</sub> concentrations at 450, 550, and 650 ppm (current concentrations are about 385 ppm, compared with pre-industrial levels of about 270 ppm). Under central projections of the IPCC, and accounting for various non-CO<sub>2</sub> greenhouse gases, these stabilization targets would result in mean projected long-term warming of about 2.0, 3.0, and 3.6°C respectively, above current levels.

Assuming globally cost-effective emission mitigation, Clarke et al. (2007) estimate that the price on CO<sub>2</sub> emissions should rise to \$40–\$95, \$5–\$30, or \$1–\$10 per ton of CO<sub>2</sub> by 2025 respectively, to be consistent with these three stabilization targets, and continue rising at around 3–5 percent a year thereafter (in real dollars).<sup>22</sup> The latter two price ranges are broadly consistent (at least in the near term) with those implied by the damage assessment studies that employ market discount rates. In striking contrast, the prices for the 450 CO<sub>2</sub> ppm target are far more aggressive.

A critical caveat to these projections is that marginal abatement costs are equated across all emissions sources worldwide and across time. To the extent, for example, that rapidly industrializing developing countries, do not fully participate in international emissions control, emissions prices in developed countries must be greater to meet the stabilization targets. Indeed, one of the modeling teams shows in subsequent work that a 450 ppm goal may not be feasible if China does not mitigate its CO<sub>2</sub> emissions before 2050 (Edmonds et al., 2007).

In summary, most analysts fall into one of two broad camps. First are those who favor relatively moderate emissions pricing in the near term, with a progressive ramp-up over time, while also preserving the flexibility to ratchet up the price as more information emerges on the risk of catastrophes. This position is based on a balancing of damage estimates (discounted at market interest rates) and abatement costs. Second are those who favor far more aggressive emissions pricing immediately, to put us on a path towards rapid stabilization of atmospheric concentrations. This position is based either on low discounting of long-range impacts and/or the view that cost/benefit analysis cannot handle the possible risks of extraordinarily catastrophic damage. The bottom line is that, following the European Union, Japanese and U.S. policy makers need, at the very least, to get a moderately scaled emissions pricing program underway.

## **B. Further Design Issues**

### *Point of Regulation*

Governments should levy a CO<sub>2</sub> tax upstream in the fossil fuel supply chain as this covers all possible sources of emissions when fuels are later combusted and therefore it exploits all potential opportunities for emissions abatement. The tax should apply to coal produced at the mine mouth, on petroleum used by refineries and imported petroleum products, and on natural gas entering the pipeline system.

---

<sup>22</sup> The widely different projections for required emissions prices stem from different assumptions about emissions growth in the absence of policy, the development of new technologies like carbon capture and storage, the scope for substituting into nuclear and renewables in power generation, and the uptake of atmospheric CO<sub>2</sub> from the oceans and biosphere.

In the European Union's ETS, as well as some cap-and trade systems proposed in U.S. climate bills, the regulatory system focuses on downstream users of fossil fuels, rather than upstream fuel producers. Downstream programs may be attractive to policy makers, as they represent a natural extension of already existing pollution regulations focusing on the power sector and major industrial emissions sources. These systems only cover only around a half of economy-wide CO<sub>2</sub> emissions, as they exclude transportation and small-scale emissions sources (Pizer, 2007). However their costs, for a given economy-wide emissions reduction, may not be that much greater than the alternative upstream program. This is because they still cover the power sector, which has a disproportionately large share of low-cost abatement opportunities. Moreover, emissions outside of the covered sector can still be regulated through other means, such as higher fuel taxes.

A further advantage of upstream programs is their administrative simplicity. An upstream CO<sub>2</sub> tax in the United States or Europe would require regulation of only around 2,000–3,000 entities (Hall, 2007). The quantity of fuels produced is readily observed and the carbon content varies moderately at most within a fuel type (for example, across bituminous, lignite, and anthracite coal). The costs of monitoring a truly comprehensive downstream program would be daunting as there are literally hundreds of millions, if not over a billion, individual greenhouse gas emission sources, ranging from transport vehicles to homes to factories to farms. For this reason the ETS is limited to 10,000 or so entities with “big smokestacks”—power plants and factories with large industrial boilers (Hall, 2007).

### *International Emissions Leakage and Competitiveness*

Energy-intensive industries competing in global markets (for example, steel, cement, aluminum) represent about one-sixth of CO<sub>2</sub> emissions for a developed country like the United States (Energy Information Administration, 2002). Morgenstern et al. (2007) find that production costs for these broad industry groups would increase by around 1–2 percent, for each \$10 increase in the CO<sub>2</sub> price, through higher input prices for electricity, fuels, and materials. This is probably minor relative to other factors governing the decision of whether to relocate plants overseas in countries where carbon is not priced (for example, exchange rate risk, greater costs of transporting products back to the domestic market). Consequently, emissions leakage—that is, the increases in emissions elsewhere as footloose firms relocate abroad—should be of relatively modest concern from an efficiency perspective.

Nonetheless, there may still be political pressure from domestic firms to prevent any “unfair” deterioration in their competitive situation compared with foreign suppliers in countries without climate policies. One way to address these concerns might be to charge fees on imported goods covering the embodied carbon in those products. Conversely, U.S. exporters selling in foreign markets might be rebated for domestic taxes paid (by upstream firms) on the embodied carbon of those products to prevent their competitiveness deteriorating. However, measuring embodied carbon in finished products, especially those produced in industrializing nations, would be contentious and possibly open to abuse by domestic industries seeking protection for other reasons. In addition, import taxes and export credits may also run afoul of international trade

agreements, or may ignite a trade war, thereby jeopardizing recent advances in trade liberalization.

### *Non-CO<sub>2</sub> GHGs*

Including non-CO<sub>2</sub> GHGs into an emissions mitigation program is important. In the United States, these gases currently account for about 20 percent of total GHGs (with all gases expressed in terms of their lifetime warming potential in CO<sub>2</sub> equivalents). At the global level non-CO<sub>2</sub> GHGs account for about a third of total GHGs, although, without mitigation policy, they will likely grow more slowly in the future than CO<sub>2</sub> emissions (Clarke et al., 2007). Some of these gases (for example, vented methane from underground coalmines, fluorinated gases used in refrigerants and air conditioners) could be monitored and incorporated into an emission tax system, based on their relative warming potential.

As regards other gases, methane and nitrous oxides from landfills, manure management, and soil management might be incorporated into an emission tax system through tax credits. Effectively, this provides a subsidy for emission reductions, appropriately set at the same rate as the corresponding emission tax. To qualify for such a subsidy, the onus falls on the individual entity to demonstrate valid emission reductions relative to what their emissions would have been without the subsidy. This takes much of the administrative burden off the regulator. Other emissions sources, which account for about a third of non-CO<sub>2</sub> GHGs in the United States, are especially difficult to monitor (for example, methane from ruminants), and may not be feasible to incorporate into an emissions tax system.

### *Incentives for Downstream Sequestration*

Extensive research is underway in the public and private sectors to develop technology that would capture a large share of CO<sub>2</sub> emissions from coal plants (and other major stationary emission sources) and store the CO<sub>2</sub> underground (for example, in depleted oil reservoirs or other geological formations), through retrofitting existing plants or reconfiguring the design of new plants. Should this technology be successfully developed, tax credits could provide incentives for its adoption. Deutsch and Moniz (2007) suggest that the price on CO<sub>2</sub> would need to be at least \$25 per ton to make capture technologies viable for new plants, and even higher for retrofitting of existing plants. An argument might be made for initially setting the tax credit per ton of CO<sub>2</sub> sequestered at or above this threshold, even if the near-term price on economy-wide emissions is below this level. This would help encourage wider diffusion of the technology, and learning-by-doing that may lead to spillover benefits to later adopters of the technology.

Biological sequestration may provide another cost-effective way to mitigate CO<sub>2</sub> emissions, although the estimates of the scope for converting cleared land into forests varies in the literature (for example, Stavins and Richards, 2005). Conceptually, farms that increased forestland coverage would receive a tax credit or subsidy, while those that shifted from forests to agriculture would pay a tax. According to Sedjo and Toman (2001) a national CO<sub>2</sub> tax system for the United States could feasibly incorporate forestry, given that transitions between forest and agricultural land in the absence of any CO<sub>2</sub> policy are relatively small. Remote sensing satellites could monitor land use changes and aircraft photography could generate estimates of stand

species composition. The appropriate CO<sub>2</sub> tax or subsidy could then be calculated based on tree species and age of the tree in the growth cycle.

### *Complementary Policies to Promote Technological Innovation*

Clearly, the key to meeting the challenge of stabilizing climate over the long run, at an acceptable cost to society, relies on the future development of technologies that will radically reduce the emission intensity of economic activity (Newell, 2008). In practice, however, designing policies to promote such R&D activity, and the diffusion of new technologies, is quite difficult.

First there is the issue of whether government should impose stiffer carbon prices to create strong incentives for induced innovation into clean technologies. This issue is not entirely resolved in the economics literature. In principle, setting taxes in excess of the marginal damage from emissions might be warranted if the losses from excessive near-term abatement were more than offset by efficiency benefits from encouraging more clean-technology R&D. This would require the returns to society from extra innovation to exceed the private returns enjoyed by the firms conducting the R&D. The social returns likely do exceed the private returns, and by a potentially large amount, due to the spillover benefits of new knowledge. In fact, empirical literature suggests that such spillovers are large in magnitude for general innovation (for example, Griliches, 1992; Mansfield, 1985; Levin et al., 1988; Jones and Williams, 1998).

Nonetheless, some studies (for example, Nordhaus, 2002; Goulder and Schneider, 1999) suggest that induced innovation has only a modest effect in setting the appropriate tax on CO<sub>2</sub>. This reflects the fact that firms already have ongoing incentives to develop more fuel efficient vehicles, power plants, and so forth and carbon pricing has a relatively moderate impact on enhancing these incentives. Moreover, extra R&D effort in the energy sector will likely crowd out socially valuable innovative effort elsewhere in the economy through the bidding up of research input prices, thereby limiting overall efficiency gains from induced innovation. Two caveats here are that the models do not really capture incentives for really transformative technologies (like carbon capture and storage and plug-in electric vehicles) and they do not include climate change benefits from other countries adopting U.S.-developed technologies.

Rather than setting stiff carbon prices, however, most analysts recommend targeting technology spillovers through more direct measures aimed at stimulating research.<sup>23</sup> Unfortunately, available literature provides limited guidance on just how much extra energy-related R&D should be stimulated and which instrument among R&D subsidies, technology prizes, and strengthened patent protection should be used (for example, Wright, 1983). Some analysts argue that, even after the development of new technologies, further incentives are needed to encourage technology diffusion, like vehicle fuel economy regulations, or energy efficiency standards for household appliances. Such policies might be warranted if there were additional market failures (for example, consumer undervaluation of energy efficiency

---

<sup>23</sup> In general, it is better to target each market failure (that is, the emissions externality and the technology spillover externality) with two separate policy instruments, rather than just one instrument (Fischer and Newell, 2008; Goulder and Schneider, 1999).

improvements). Whether such additional market failures exist and their potential magnitude, however, remains an unsettled issue in the literature.

### **C. Summary**

At a domestic level, designing a CO<sub>2</sub> tax is fairly straightforward, especially if imposed upstream in the fossil fuel supply chain—as a carbon-added tax. Incorporating at least some non-CO<sub>2</sub> GHGs into the tax system is quite feasible, as is providing incentives for downstream geological and biological CO<sub>2</sub> sequestration. The main difficulties lie in deciding the tax level and how rapidly it should escalate over time, as well as ensuring productive use of revenues, in the presence of pressure for spending to satisfy special interests.

## **IV. CO<sub>2</sub> TAXES AT A GLOBAL LEVEL**

We now turn to issues in the development of an international architecture based on CO<sub>2</sub> pricing. In particular, we discuss implementation issues and the relative ease or difficulty of reaching international agreements with tax and quantity-based instruments. We focus on a multilateral “top-down” approach to climate policy agreements where countries attempt to reach agreement on CO<sub>2</sub> tax rates they will each impose, or targets for emissions control. Many of the issues are not so pressing if international climate policy emerges unilaterally from the bottom up, with countries developing their own targets and policy instruments, either to follow, or set an example to, other countries.

To be successful, any international climate agreement needs to meet a number of key criteria (Aldy and Stavins, 2007a). These include cost-effectiveness, equity, broad participation, ease of reaching agreement over taxes or emissions targets, verification of member compliance with the agreement, and domestic institutional capability to implement the policy. We take each of these in turn. As we discuss, the first three criteria for a successful climate control agreement could, in principle, be met under either tax- or allowance-based approaches. And although it may be more difficult both to reach, and implement, an international permit trading system, concerns about emissions control effectiveness being compromised by other surreptitious policy adjustments pose greater challenges under the tax-based regime.<sup>24</sup>

### **A. Cost-Effectiveness**

At any given point in time, cost-effectiveness requires that the marginal costs of abatement are roughly the same across different countries. In a dynamic sense, it also requires that marginal abatement costs are roughly equated, in present value terms, across current and future periods (or equated with marginal emissions damages under a welfare maximizing approach).

The cost-effectiveness condition can be met if all countries impose the same tax rate on CO<sub>2</sub> (and the same tax on other GHGs and credits for sequestration) and the tax rate rises at the rate

---

<sup>24</sup> As pointed to us by Jon Strand, the potential for rent extraction by the OPEC cartel is greater when facing a cap set by energy-importing countries than when facing an importer carbon tax. The cap is an effective coordination mechanism.

of interest over time (or with the growth rate in marginal emissions damages).<sup>25</sup> Under an international cap-and-trade system, marginal abatement costs are equated across different regions at a point in time if the international regime fully integrates efficient domestic allowance trading markets. Frictionless borrowing and banking provisions help to equate marginal abatement costs in the current period with those expected in future periods. Under either the tax or allowance system, promoting dynamic cost-effectiveness requires that policies are set in advance over a long time horizon. If policy commitment periods are short, there is the danger that policy stringency will significantly diverge across different commitment periods, causing marginal abatement costs to differ across time. Moreover, a stable, long-term policy framework will help firms make efficient decisions with regard to major R&D or technology investments with long-term payoffs. Finally, a cost-effective agreement can promote broader participation—by limiting the downside risks of noncompliance—and deeper participation—by facilitating more aggressive policy goals in the future.

## B. Equity

Usually, an equitable agreement among member countries means that more advanced, wealthier members bear a relatively greater cost burden than less developed, poorer nations. The burden of emissions abatement costs is likely to differ dramatically across different regions under an internationally harmonized CO<sub>2</sub> price. In fact, as suggested by Table 2, emerging and developing countries, especially China, would likely bear a disproportionately larger cost than the United States and Western Europe, given the higher CO<sub>2</sub> to GDP intensities in the former countries.

**Table 2. Projected Emissions of CO<sub>2</sub> from Fossil Fuels as a Proportion of Real GDP**

<i>Year</i>	<i>2002</i>	<i>2101</i>	<i>2020</i>	<i>2030</i>	<i>2040</i>
United States	0.55	0.51	0.47	0.45	0.43
Japan	0.30	0.28	0.28	0.27	0.26
Eastern Europe	0.85	0.77	0.69	0.63	0.58
Western Europe	0.37	0.35	0.31	0.29	0.26
Industrial (Annex 1) countries	0.51	0.47	0.43	0.40	0.38
China	3.11	2.48	2.69	2.72	2.72
Other developing and emerging economies	0.87	0.75	0.71	0.70	0.69
OPEC economies	1.82	1.50	1.36	1.34	1.31
Non-Annex 1 economies	1.29	1.12	1.14	1.12	1.08
World	0.67	0.61	0.63	0.63	0.63

Source: International Monetary Fund (2008), Table 4.5.

Notes: The ratios refer to metric tons of carbon dioxide per thousand 2000 US\$ using market exchange rates. Annex I refers to the group of 40 industrial countries that were signatories to the 1997 Kyoto Agreement to control GHG emissions. Non-Annex I countries refers to all other developing and industrializing nations.

<sup>25</sup> Ideally one would like all agents to face the same unified emissions price, however, since there are distortions in foreign exchange markets—from tariffs on trade to licensing, official intervention and so forth—a single rate defined, say, in US dollars, may translate into different rates in different countries.

To preserve the cost-effectiveness criteria, equity concerns would ideally be addressed through inter-country side payments or other compensation (rather than allowing the policy stringency, and hence marginal abatement costs, to differ across countries). Under a CO<sub>2</sub> tax system, a portion of the revenues raised in wealthier nations might be redistributed to the relatively poorer countries, through some agreed formula, that accounts for measures of per capita income, emissions intensities, and perhaps historical contributions to atmospheric GHG accumulations. An analog to direct side payments exists under the cap-and-trade approach, where wealthier countries take on more stringent emission caps, but they can exceed these targets by purchasing emission allowances from poorer countries with relatively lax targets.

### **C. Broad Country Participation**

Obviously, the more countries that participate, the more effective the agreement will be in reducing global emissions. Moreover, broad participation reduces the risk of emission leakage from energy-intensive firms within the covered region relocating to countries with no climate policy. The breadth of participation reflects important ex ante and ex post policy decisions.

The first, ex ante dimension focuses on the number of countries joining the climate policy coalition. Presumably, these countries value the benefits of participation (and doing something about climate change) more than their burden of costs, and vice versa for those not initially participating. Enticing new countries into the agreement over time may again require direct side payments or initially allowing them less onerous emissions targets. More generally, some countries may remain outside the formal emission mitigation agreement, but be included in a looser, informal group with some, more ad hoc, incentives for emission mitigation. For example, some of the revenues from an international CO<sub>2</sub> tax (or from allowance auctions) could finance technology transfer to developing countries.

The second, ex post dimension is the possibility that individual countries in the agreement will not comply with their obligations, or even pull out of the agreement altogether. To deter this may require penalties for noncompliance. For example, countries make an upfront deposit into a fund during the first phase of the policy period (perhaps out of revenues from CO<sub>2</sub> taxes or allowance auctions) and the fund returns the proceeds (with interest) at the end of the policy period, but only to those countries remaining in the agreement. Others have suggested the use of trade sanctions to penalize noncomplying and nonparticipating countries (Nordhaus, 1998; Aldy, Orszag, and Stiglitz, 2001).

### **D. Reaching Agreement on Taxes or Targets**

In a Kyoto-like system, countries have to agree on a set of *national* emission targets. Initially, these targets can be set relative to actual emissions in a recent 'reference' year; the Kyoto Protocol stipulates 1990 as its reference year. This focus on targets as a function of a historic reference year presents problems for comparing effort and burdens across countries that may experience very different baseline (no new policy) emission growth rates. Thus, reducing emissions 7 per cent below 1990 levels over 2008–2012, as the Kyoto Protocol would have required the United States (had it not withdrawn from the treaty) would have been quite costly, as emissions have grown rapidly since 1990. Similar targets for the United Kingdom and

Germany are much less onerous, since their emissions declined in the 1990s with the closure of uneconomic coalmines and manufacturing facilities. Under a tax-based regime there is only one variable to negotiate over—the tax rate on CO<sub>2</sub> that countries should impose (along with a rule for tightening it over time). This avoids the haggling over country-level targets endemic to a Kyoto-style approach. Of course, if some countries decide not to participate in a harmonized CO<sub>2</sub> tax regime, then they are implicitly imposing a different (zero) tax on their sources of greenhouse gas emissions. Explicit transfers (as discussed above) or issue linkage (such as providing benefits through the trade or development policy agendas) may be necessary to discourage developing countries from advocating for differential tax rates.

### **E. Institutional Capability in Developing and Industrializing Nations**

Variability in baseline emissions also reflects substantial uncertainty in forecasting emissions. Many developing countries lack the capacity to estimate future emissions in order to assess the implicit stringency of quantitative targets. This motivates the primary developing country objection that emission caps could constrain economic growth. Even if developing countries could take on quantitative caps, implementing them through a domestic cap-and-trade system may not be feasible. Few developing countries have sufficiently strong environmental ministries to design a cap-and-trade regime. Moreover, weak and less than fully independent judicial institutions raise questions about the enforcement of allowances as property rights. The prospect of free allowance allocations in nations with limited or mixed experiences with privatization also suggests the value of the tax alternative. From an institutional perspective, much more powerful finance ministries could administer a carbon tax. In some countries, the finance ministry could simply integrate the carbon tax with existing taxes on fossil fuel purchasers. This approach would also take advantage of existing monitoring of energy production, imports, exports, and consumption. Some finance ministries in developing countries may advocate for CO<sub>2</sub> taxes as a new source of badly need revenue (Cooper, 2007).

Employing a policy (a CO<sub>2</sub> tax) instead of a goal (a quantitative emission target) may also be a more appropriate way to move forward with country-level commitments. National governments should commit to what they can directly control. Firms and individuals undertake activities that emit GHGs; governments are responsible for a small share of emissions. Focusing on policy actions may provide for a more credible negotiation than emission goals for which some countries may have no idea how to attain.

### **F. Verification**

The main drawback of the tax-based approach at the international level is that it could be undermined by “fiscal cushioning”: the reduction of other taxes borne by sources of GHGs to partly offset the burden of a CO<sub>2</sub> tax (Wiener, 1999). In some cases, offsetting reductions in other energy taxes are transparent (for example, a reduction in gasoline tax), but not in others (for example, complex tax loopholes for expensing of capital or technology investments).<sup>26</sup> The same problem does not apply under emission allowance systems, since countries still have to meet

---

<sup>26</sup> Sweden reduced some of its energy taxes on the most energy-intensive industries when it implemented its carbon tax (Daugbjerg and Pedersen, 2004).

their national emissions quotas, regardless or whether they introduce compensatory measures for energy or not.

A possible response to the risk of fiscal cushioning is to develop a broader measure of a country's effective CO<sub>2</sub> tax, accounting for preexisting energy taxes or subsidies. For example, the 40-cent per gallon gasoline tax in the United States (on average across the states) is equivalent to a \$45 tax on CO<sub>2</sub> from the auto sector, or about \$9 per ton on nationwide emissions. Similarly, estimated government revenues forgone from the favorable tax treatment of energy industries could be expressed per ton of CO<sub>2</sub>. In principle, all countries might be pressured or required to increase this broader CO<sub>2</sub> tax at the same rate over time. Therefore, any reductions in other energy taxes would require an offset through a higher formal tax on CO<sub>2</sub>.

This approach, however, raises three problems. First, it is not always easy to measure the magnitude of complex and opaque systems of energy tax preferences, although international inspection of taxing agencies and the accounts of energy companies would help. Second, broader energy taxes might offset externalities. For example, Parry and Small (2005) estimate that gasoline taxes in the United States fall well below (second-best) levels that might be warranted by traffic congestion, accident, and local pollution externalities. Effectively, this means that gasoline is actually subsidized, not taxed. Third there are a wide variety of nontax regulations that further penalize, or favor, energy sectors, such as price regulation in the power sector, and standards for emission rates and fuel economy on automobiles. In principle, the tax equivalent of these other regulations need to be quantified, along with the externalities, and then converted into their CO<sub>2</sub> tax or subsidy equivalent to obtain an unbiased measure of overall CO<sub>2</sub> taxes. These procedures would be quite detailed and controversial.

These considerations suggest the need for two kinds of systematic and regular country reviews. First, the reviews would assess whether governments undertake explicit (by changing other tax laws) or implicit (by changing tax subsidies and other regulations) fiscal cushioning for various sources subject to the CO<sub>2</sub> tax policy. Second, the reviews would evaluate progress on mitigating emissions, compare efforts across countries, and assess the adequacy of the aggregate effort in combating climate change. These evaluations should be conducted by an independent, international institution, akin to the IMF's Article IV consultations and the OECD's annual review of member countries' economic policies (Aldy and Stavins, 2007b). While the reviews may not on their own be sufficient to deter fiscal cushioning, the spotlight on such efforts could draw condemnation from other countries. The pressure from other countries could establish a norm against fiscal cushioning and promote broad, if occasionally incomplete, participation.

## V. CONCLUDING REMARKS

The success of domestic and international efforts to slow global climate change will depend on how policies meet key criteria, such as keeping down overall policy costs, satisfying distributional objectives, dealing with economic variability and disruptions, providing incentives for clean technology development, and the ease of policy coordination and verification among different countries. In principle, (revenue-neutral) CO<sub>2</sub> taxes appear to have a number of advantages over cap-and-trade systems, but the devil lies in the details of the implementation. At the domestic level, an appropriately designed cap-and-trade system—with allowance auctions

and smart revenue recycling as well as mechanisms to contain costs, such as a safety valve or banking and borrowing—could mimic many of the benefits of a CO<sub>2</sub> tax. Even so, at the international level, a CO<sub>2</sub> tax might be more effective at promoting broad country participation, especially among developing countries with limited institutions for implementing a new permit trading system.

Cap-and-trade systems that emerge in practice may also contain serious design flaws. For example, although the European Trading Scheme will transition to (nearly) full allowance auctions, it is not yet clear whether all European Union governments will use the revenues productively. And while the policy now permits full allowance banking, it still prohibits allowance borrowing across commitment periods; in the near term, this leaves it exposed to the risks of large disruptions, for example, from fuel price shocks. If such a disruption occurs, that could undermine popular support for future, progressive tightening of the emissions cap, and for the introduction of similar schemes in other countries. Until allowance systems become really well designed, and have proven to withstand the test of time, the (revenue-neutral) CO<sub>2</sub> tax remains an attractive alternative, and possibly the more likely policy to facilitate the durable and substantial agreement needed to seriously slow global warming over the coming decades.

## REFERENCES

- Aldy, Joseph E., Alan J. Krupnick, Richard G. Newell, Ian W.H. Parry, and William A. Pizer. 2008. "Climate Economics and Policy." RFF Discussion Paper. Washington, DC: Resources for the Future.
- Aldy, Joseph E., Peter R. Orszag, and Joseph E. Stiglitz. 2001. "Climate Change: An Agenda for Global Collective Action." AEI-Brookings Joint Center on Regulatory Affairs Related Publication. Washington, DC: AEI.
- Aldy, Joseph E., and Robert N. Stavins. 2007a "Introduction: International Policy Architectures for Global Climate Change." In: J.E. Aldy and R.N. Stavins, eds., *Architectures for Agreement: Addressing Global Climate Change in the Post-Kyoto World*. Cambridge, UK: Cambridge University Press.
- . 2007b "Architectures for an International Global Climate Change Agreement: Lessons for the Policy Community." In: J.E. Aldy and R.N. Stavins, eds., *Architectures for Agreement: Addressing Global Climate Change in the Post-Kyoto World*. Cambridge, UK: Cambridge University Press.
- Austin, David, and Terry Dinan. 2005. "Clearing the Air: The Costs and Consequences of Higher CAFE Standards and Increased Gasoline Taxes." *Journal of Environmental Economics and Management* 50: 562–82.
- Bosello, Francesco, Carlo Carraro, and Marzio Galeotti. 2001. "The Double Dividend Issue: Modeling Strategies and Empirical Findings." *Environment and Development Economics* 6(1): 9–45.
- Bovenberg, A. Lans, and Lawrence H. Goulder. 1997. "Costs of Environmentally Motivated Taxes in the Presence of Other Taxes: General Equilibrium Analyses." *National Tax Journal* L: 59-87.
- . 2001. "Neutralizing the Adverse Industry Impacts of CO<sub>2</sub> Abatement Policies: What Does It Cost?" In: C. Carraro and G. Metcalf, eds., *Behavioral and Distributional Effects of Environmental Policy*. Chicago: University of Chicago Press.
- . 2002. "Environmental Taxation and Regulation." In: A. Auerbach and M. Feldstein, eds., *Handbook of Public Economics*. New York: North Holland.
- Bruvoll, Annegrete, and Bodil Merethe Larsen. 2004. "Greenhouse Gas Emissions in Norway: Do Carbon Taxes Work?" *Energy Policy* 32: 493–505.
- Burtraw, Dallas, Karen Palmer, Ranjit Bharvirkar, and Anthony Paul. 2002. "The Effect on Asset Values of the Allocation of Carbon Dioxide Emission Allowances." RFF Discussion Paper 02-15. Washington, DC: Resources for the Future.

- CEC (Commission of the European Communities). "20 20 by 2020: Europe's Climate Change Opportunity." Communication from the Commission to the European Parliament, the Council, The European Economic and Social Committee, and the Committee of the Regions. Commission of the European Communities.
- Clarke, Leon E., James A. Edmonds, Henry Jacoby, Hugh M. Pitcher, John M. Reilly, and Richard G. Richels. 2007. *Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations*. Washington, DC: U.S. Climate Change Science Program.
- Cooper, Richard N. 2007. "Alternatives to Kyoto: the Case for a Carbon Tax." In: J.E. Aldy and R.N. Stavins, eds., *Architectures for Agreement: Addressing Global Climate Change in the Post-Kyoto World*. Cambridge, UK: Cambridge University Press.
- Daugbjerg, Carsten, and Anders Branth Pedersen. 2004. "New Policy Ideas and Old Policy Networks: Implementing Green Taxation in Scandinavia." *Journal of Public Policy* 24(2): 219–249.
- Deutsch, John, and Ernest J. Moniz. 2007. *The Future of Coal: Options for a Carbon-Constrained World*. Cambridge, MA: MIT Press.
- Dinan, Terry M., and Diane L. Rogers. "Distributional Effects of Carbon Allowance Trading: How Government Decisions Determine Winners and Losers." *National Tax Journal* LV:199–222.
- Edmonds, J., L. Clarke, J. Lurz, and M. Wise. 2007. "Stabilizing CO<sub>2</sub> Concentrations with Incomplete International Cooperation." Report PNNL-16932. Richland, WA: Pacific Northwest National Laboratory.
- Energy Information Administration. 2008. *Annual Energy Outlook 2008*. Washington, DC: U.S. Department of Energy.
- Fischer, Carolyn, and Richard G. Newell. 2008. "Environmental and Technology Policies for Climate Mitigation." *Journal of Environmental Economics and Management* 55: 142–162.
- Goulder, Lawrence H. 1995. "Environmental Taxation and the Double Dividend: A Reader's Guide" *International Tax and Public Finance* 2: 157–183.
- Goulder, Lawrence H. and Ian W.H. Parry. 2008. "Instrument Choice in Environmental Policy." *Review of Environmental Economics and Policy* (forthcoming).
- Goulder, Lawrence H., and Stephen H. Schneider. 1999. "Induced Technological Change and the Attractiveness of CO<sub>2</sub> Emissions Abatement Policies." *Resource and Energy Economics* 21: 211–53.
- Government of British Columbia. 2008. "Backgrounder: BC's Revenue-Neutral Carbon Tax." *Balanced Budget 2008*. Internet: [www.gov.bc.ca/bcbudget](http://www.gov.bc.ca/bcbudget).

- Government of Sweden. 2005. *Sweden's Fourth National Communication on Climate Change*. Stockholm: Ministry of Sustainable Development.
- Griliches, Zvi. 1992. "The Search for R&D Spillovers." *Scandinavian Journal of Economics* 94 (Supplement): S29–S47.
- Hall, Daniel. 2007. "By the Numbers: Greenhouse Gas Emissions and the Fossil-Fuel Supply Chain in the United States." In: R.J. Kopp and W.A. Pizer, eds., *Assessing U.S. Climate Policy Options*. Washington, DC: Resources for the Future.
- Hepburn, Cameron. 2006. "Regulating by Prices, Quantities or Both: An Update and an Overview." *Oxford Review of Economic Policy* 22: 226–247.
- Intergovernmental Panel on Climate Change. 2007. *Climate Change 2007: The Physical Science Basis*. Cambridge, UK: Cambridge University Press.
- International Monetary Fund. 2008. "Climate Change and the Global Economy." Chapter 4 in the *World Economic Outlook*. Washington, DC: IMF.
- Jacoby, H.D., and A.D. Ellerman. 2004. "The Safety Valve and Climate Policy." *Energy Policy* 32(4): 481–91.
- Jones, Charles I., and John C. Williams. 1998. "Measuring the Social Return to R&D." *Quarterly Journal of Economics* 113: 1119–1135.
- Kopp, Raymond J., and William A. Pizer. 2007. *Assessing U.S. Climate Policy Solutions*. Washington, DC: Resources for the Future.
- Kopp, Raymond J., Richard D. Morgenstern, and William A. Pizer. 1997. "Something for Everyone: A Climate Policy that Both Environmentalists and Industry Can Live With." *Weathervane*, Washington, DC: Resources for the Future, September 29.
- Levin, Richard C., Alvin K. Klevorick, Richard R. Nelson, and Sidney G. Winter. 1988. "Appropriating the Returns from Industrial Research and Development." *Brookings Papers on Economic Activity* 3 Special Issue on Microeconomics: 783–820.
- Mansfield, Edwin. 1985. "How Fast Does New Industrial Technology Leak Out?" *Journal of Industrial Economics* 34: 217–33.
- Massachusetts Division of Energy Resources. *Renewable Portfolio Standard*. <http://www.mass.gov/doer/rps/index.htm> (Accessed on March 3, 2008), 2008.
- McKibbin, Warwick J. and Peter J. Wilcoxon. 2007. "A Credible Foundation for Long-Term International Cooperation on Climate Change." In: J.E. Aldy and R.N. Stavins, eds., *Architectures for Agreement: Addressing Global Climate Change in the Post-Kyoto World*. Cambridge, UK: Cambridge University Press.

- McKibbin Warwick J., and Peter J. Wilcoxon. 1997. "A Better Way to Slow Global Climate Change." Brookings Policy Brief, no. 17. Washington, DC: The Brookings Institution.
- Mendelsohn, R. 2005. "Climate Critique" *Harvard International Review* 26: 4–5.
- Metcalf, Gilbert E. 2007. "A Carbon Tax Swap as a Response to Global Warming." Department of Economics Discussion Paper. Medford, MA: Tufts University.
- Morgenstern, Richard D., Joseph E. Aldy, Evan M. Herrnstadt, Mun Ho, and William A. Pizer. 2007. "Competitiveness Impacts of Carbon Dioxide Pricing Policies on Manufacturing." In: R.J. Kopp and W.A. Pizer, eds., *Assessing U.S. Climate Policy Options*. Washington, DC: Resources for the Future.
- Newell, Richard G. 2008. "An Innovation Strategy for Climate Change Mitigation." Working Paper. Durham, NC: Duke University.
- Newell, Richard G. and William A. Pizer. 2003. "Regulating Stock Externalities Under Uncertainty." *Journal of Environmental Economics and Management* 45(2): 416–432.
- Nordhaus, William D. 2008. *A Question of Balance: Economic Modeling of Global Warming*. New Haven, CT: Yale University Press.
- . 2007. "The Stern Review on the Economics of Climate Change." *Journal of Economic Literature* XLV: 686–702.
- . 2002. "Modeling Induced Innovation in Climate-Change Policy." In: A. Grubler, N. Nakicenovic and W.D. Nordhaus, eds., *Technological Change and the Environment*. Washington, D.C.: Resources for the Future Press.
- . 1998. "Is the Kyoto Protocol a Dead Duck? Are There Any Live Ducks Around? Comparison of Alternative Global Tradable Emissions Regimes." Department of Economics Working Paper. New Haven, CT: Yale University, New Haven, 31 July.
- Nordhaus, William D., and Joseph Boyer. 2000. *Warming the World: Economic Models of Global Warming*. Cambridge, MA: MIT Press.
- Parry, Ian W.H., and Antonio M. Bento. 2000. "Tax Deductions, Environmental Policy, and the 'Double Dividend' Hypothesis." *Journal of Environmental Economics and Management* 39: 67–96.
- Parry, Ian W.H., Roberton C. Williams III, and Lawrence H. Goulder. 1999. "When Can Carbon Abatement Policies Increase Welfare? The Fundamental Role of Distorted Factor Markets." *Journal of Environmental Economics and Management* 37: 52–84.
- Parry, Ian W.H., Hilary Sigman, Margaret Walls, and Roberton C. Williams. 2006. "The Incidence of Pollution Control Policies." In: T. Tietenberg and H. Folmer, eds., *The International Yearbook of Environmental and Resource Economics 2006/2007*. Northampton, MA: Edward Elgar.

- Parry, Ian W.H., and Kenneth A. Small. 2005. "Does Britain or the United States Have the Right Gasoline Tax?" *American Economic Review* 95: 1276–1289.
- Pizer, William A. 2007. "Scope and Point of Regulation for Pricing Policies to Reduce Fossil Fuel CO<sub>2</sub> Emissions." In: R.J. Kopp and W.A. Pizer, eds., *Assessing U.S. Climate Policy Options*. Washington, DC: Resources for the Future.
- . 2002. "Combining Price and Quantity Controls to Mitigate Global Climate Change." *Journal of Public Economics* 85: 409–34.
- Sedjo, Roger A., and Michael Toman. 2001. "Can Carbon Sinks Be Operational?" RFF Discussion Paper 01–26. Washington, DC: Resources for the Future.
- Smith, Anne E., Martin E. Ross, and W. David Montgomery. 2002. "Implications of Trading Implementation Design for Equity-Efficiency Tradeoffs in Carbon Permit Allocations." Working paper. Washington, DC: Charles River Associates.
- Stavins, Robert N. 1996. "Correlated Uncertainty and Policy Instrument Choice." *Journal of Environmental Economics and Management* 30: 218–32.
- . 2007. "Market-Based Environmental Policies: What Can We Learn From U.S. Experience (and Related Research)?" In: J. Freeman and C. Kolstad, eds., *Moving to Markets in Environmental Regulation: Lessons from Twenty Years of Experience*. New York: Oxford University Press.
- Stavins, Robert N., and Kenneth R. Richards. 2005. *The Cost of U.S. Forest-based Carbon Sequestration*. Arlington, VA: Pew Center on Global Climate Change.
- Stern, Nicholas. 2007. *The Economics of Climate Change*. Cambridge, UK: Cambridge University Press.
- Tol, Richard S.J. 2007. "The Social Cost of Carbon: Trends, Outliers and Catastrophes." Economics Discussion Paper No. 2007-44. Kiel, Germany: Kiel Institute for the World Economy.
- U.S. National Academy of Sciences. 2008. *Understanding and Responding to Climate Change*. Washington DC: National Academy Press.
- Vehmas, Jarmo. 2005. "Energy-Related Taxation as an Environmental Policy Tool—The Finnish Experience 1990–2003." *Energy Policy* 33: 2175–2182.
- Weitzman, Martin L. 1974. "Prices vs. Quantities." *Quarterly Journal of Economics* 41: 477–91.
- . 2008. "On Modeling and Interpreting the Economics of Catastrophic Climate Change." Department of Economics Working Paper. Cambridge, MA: Harvard University.
- Weyant, John P., and Jennifer Hill. 1999. "The Costs of the Kyoto Protocol: A Multi-Model Evaluation, Introduction and Overview." *The Energy Journal* Kyoto Special Issue: vii–xliv.

Wiener, Jonathan B. 1999. "Global Environmental Regulation: Instrument Choice in Legal Context." *Yale Law Journal* 108: 677–800.

Wright, Brian D. 1983. "The Economics of Invention Incentives: Patents, Prizes, and Research Contracts." *American Economic Review* 73(4): 691–707.