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A PRACTICAL GUIDE TO THE ECONOMICS OF CARBON PRICING

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SUMMARY

Canadian economists, politicians and even environmentalists are lining up enthusiastically behind pricing carbon as the solution to controlling greenhouse gas emissions in this country. Pricing carbon (or, more accurately, pricing carbon dioxide) is not just a fashionable policy approach; it is the most efficient way we have to ration emissions, as it allows emitters — businesses and consumers — to make the most rational decisions about where it makes economic sense to curtail carbon and where it does not. Painfully costly command-and-control reductions make little sense in Canada, given our marginal contribution to global emissions. When practiced globally, a carbon price deals with Canadian emitters as fairly as it does others.

However, a beneficial outcome is not guaranteed: certain rules must be observed in order for carbon pricing to have its intended effect of achieving the optimal balance between emission reduction and economic growth. First and foremost, carbon pricing only works in the absence of any other emission regulations. If pricing is layered on top of an emission-regulating regime already in place (such as emission caps or feed-in-tariff programs), it will not only fail to produce the desired effects in terms of emission rationing, it will have distortionary effects that cause disproportionate damage in the economy. Carbon taxes are meant to replace all other climate-related regulation, while the revenue from the taxes should not be funnelled into substitute goods, like renewable power (pricing lets the market decide which of those substitutes are worth funding) but returned directly to taxpayers.

The price of carbon is set according to what is known as the "social cost of carbon" — the quantified value of the impact that an emitted tonne of carbon today will have on humans in the future (adjusted to present value). That cost is not limitless; there is a point at which the cost of abating a tonne of carbon outweighs the cost of the impact that same tonne will have in the future (and some of that impact may be positive, not necessarily negative). Therefore,

another important rule for creating a proper carbon-pricing system is to be as careful as possible in estimating the social cost of carbon. Estimates are all we have, and they vary wildly, from negative — meaning any carbon price is too high — to hundreds of dollars per tonne. Minor adjustments to the calculation's inputs, such as the discount rate used and fluctuating estimates about climate sensitivity, produce dramatically different estimates. The social cost of carbon must be set with extreme prudence in order to set a reasonable carbon price.

Whatever the carbon price, it will necessarily detract some degree from economic growth. But when a carbon tax is added in the presence of other taxes, such as income, sales and corporate taxes, its effect will be even more harmful, due to the compounded burden on economic activity. As a result, whatever the social cost of carbon is determined to be, the carbon price must be discounted below it by the marginal cost of public funds (MCPF) — that is, the economic cost of the government raising an additional dollar of tax, on top of what is already being raised. This varies by province, but estimates suggest that in Canada, the optimal carbon tax should be about half of the estimated social cost of carbon.

Finally, it needs to be remembered that carbon pricing works because it is a market-based policy: it works with market forces, not against them. But that means the policy maker needs to let the market play its role. Choosing the price means the market will set the quantity, and vice-versa. In response to a well-designed carbon price, the market may only reduce emissions a little, especially in the short term. Policy makers need to resist the temptation to reintroduce command-and-control rules and arbitrary quantity targets, which will simply unravel the gains from adopting the policy in the first place.

There may be many reasons to recommend carbon pricing as climate policy, but if it is implemented without diligently abiding by the principles that make it work, it will not work as planned, and the harm to the Canadian economy could well outweigh the benefits created by reducing our country's already negligible level of global CO_2 emissions.

1. INTRODUCTION: KEY ASPECTS OF THE CARBON-PRICING ISSUE

"One cannot have cheap energy without carbon dioxide emissions."
Richard Tol[1]

1.1 Pricing Carbon (Dioxide)

Carbon pricing has moved to the centre of national policy discussion. Governments at all levels are pursuing it, think tanks are studying it, and a steady stream of new commentary on it appears weekly. There is a palpable enthusiasm for the view that carbon pricing can accomplish some hitherto unattainable climate goals while minimizing the risk to economic growth. The underlying concept is not new: economists have been studying emission pricing since the 1920s, and have developed a deep understanding of the complexities involved. Pricing instruments can indeed achieve environmental goals at lower costs than traditional command-and-control instruments can. But to yield net benefits, implementation has to be done right, and proper attention needs to be paid to some technical details that are largely being overlooked in the current conversation. This paper discusses some of the key theoretical issues and explains how they apply to the practical design of carbon pricing.

Carbon dioxide (CO_2) is released whenever fossil fuels are burned. On a per-unit of energy basis, coal releases the most, then oil, then natural gas.[2] "Carbon pricing" refers to the use of a tax or tradable permit to impose on fuel users a cost per tonne of CO_2 emissions, thereby internalizing to the emitter the social costs associated with the emitting activity. While it is common to refer to the pollutant of interest as "carbon," we are actually interested in CO_2, and the distinction is important. A molecule of CO_2 is three-elevenths carbon by molecular weight. So a tonne of CO_2 contains 0.27 tonnes of carbon. If a tax of $20 per tonne is placed on CO_2, this corresponds to a tax of $20 on 0.27 tonnes of carbon, or $74 per tonne of carbon.

The distinction also matters for measuring damages and the costs of abatement options. "Carbon pollution" (namely carbon monoxide, or CO, carbon particulates and carbonaceous aerosols) harms local air quality, whereas CO_2 emissions do not. Very few places in the world even measure CO_2 concentrations[3] because they are not of local concern. CO_2 is not a contributor to smog nor does it pose any health problems even at levels far above current concentrations.[4] The potential harm is associated with changes in the global climate, which is affected by the global average concentration.

Global climatic changes translate into specific local economic impacts, but these vary widely by sector and location and are difficult to forecast. It is not the case that all such changes will be large or even harmful in specific regions. The most recent report of the Intergovernmental Panel on Climate Change (Working Group II, Chapter 10, which summarizes research on impacts of climate change) concludes that the economic impact of most such changes will be a mix of positive and negative effects with the balance likely negative, and generally will be small relative to the impacts of other economic drivers as long as warming is not at the

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1 Richard S.J. Tol, "The Economic Effects of Climate Change," *Journal of Economic Perspectives* 23, 2 (Spring 2009): 29-51.

2 A.P. Jaques, *National Inventory of Sources and Emissions of Carbon Dioxide, 1987* (Ottawa: Environment Canada, 1990).

3 For example, Ontario maintains a network of 40 air-quality monitoring sites (airqualityontario.com) but none measure CO_2. The current global network of monitoring sites for CO_2 can be seen at http://www.esrl.noaa.gov/gmd/dv/iadv.

4 Commercial greenhouses artificially boost CO_2 levels to about triple the outdoor level to enhance plant growth, and humans exhale air containing CO_2 at 40,000 parts per million, about 100 times the level in the atmosphere.

high end of the potential range. The average potential welfare changes are small and possibly positive for warming below 2 C and they change to an expected loss of 0.2 to 3.0 per cent of income for warming of 2 to 3 C.[5] Little work has been done on aggregate effects of warming above that rate.

Unlike carbon pollution, there are relatively few options for controlling release of CO_2. CO and particulates can be reduced using end-of-pipe abatement equipment, such as catalytic converters on cars and scrubbers on power plants, but these do not reduce CO_2, the volume of which is almost entirely determined by the amount of carbon in the fuel regardless of how it is burned.[6] The most reliable way to reduce CO_2 emissions is to cut fuel use.

Throughout this report I will refer to carbon dioxide (or CO_2) when referring to the emissions of interest. I will defer to common practice and use the shorthand "carbon tax" and "carbon pricing." But the reader should bear in mind that the price is placed on CO_2, not "carbon."

1.2 Emissions versus Concentrations

CO_2 emissions from fossil-fuel burning is a small but important part of a much larger natural carbon cycle. About 44,000 gigatonnes of carbon-equivalent (GtC) are stored in the atmosphere and oceans, mostly in the form of CO_2.[7] Between 150 and 200 GtC are released naturally each year through oceanic outgassing and land-based processes like plant decay and animal respiration. A variable but roughly equivalent amount is absorbed each year by the land and oceans, with a small net loss from the atmosphere because the formation of deep ocean sediment sequesters some carbon permanently. Global fossil fuel consumption and cement manufacture[8] released about 9.8 GtC in 2013, up from 6.1 GtC in 1990.[9] Of this, about 5 GtC is naturally sequestered through plant growth and oceanic uptake while the remainder, about 5 GtC, adds to the atmospheric stock.[10]

In the case of conventional air pollution, it is the local concentration that affects human welfare. Policy affects the flow of emissions, but the linkage between the two is reasonably direct. Once the flow of emissions is reduced, the local concentration drops rapidly, usually on a time scale of a few days. Local emission reductions therefore improve local environmental quality in a short time frame.

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5 D.J. Arent et al, "Key economic sectors and services," in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. C. B. Field et al. (Cambridge University Press, Cambridge, 2014), 659-708, Figure 10-1.

6 G. Marland and R.M. Rotty, "Carbon dioxide emissions from fossil fuels: A procedure for estimation and results for 1950-82," *Tellus* 36, B (1984): 232-61.

7 Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the IPCC* (Cambridge: Cambridge University Press, 2013), Chapter 6.

8 This discussion concerns the global carbon cycle involving CO_2. Some inventories (such as Environment Canada's) present total GHG emissions including non-CO_2 sources as well, including methane and nitrous oxide. At the global level, land-use change emits about 1 GtC annually, but this is more than offset by a 2.5 GtC carbon sink on land (see IPCC, *Climate*, Figure 6.1 and Table 6.1).

9 T.A. Boden, G. Marland and R.J. Andres, *Global, Regional, and National Fossil-Fuel CO2 Emissions* (Oak Ridge, Tenn.: U.S. Department of Energy, 2015). Data online at http://cdiac.ornl.gov/trends/emis/overview_2013.html. Note that the emissions being referred to here are CO_2, but they are translated into common units of "carbon equivalent" so that they match the units used for the carbon inventory in the atmosphere and oceans.

10 IPCC, *Climate*, Chapter 6, Figure 6.1. Note that fossil-fuel consumption and cement manufacture are the dominant sources of CO_2 emissions to the atmosphere.

Not so with CO_2, since the effect operates through the global, rather than the local, concentration. The global carbon cycle is vast and slow, so a change in local emissions today will only have a very small global effect, and only after a long time lag. About 20 years after a pulse (release) of CO_2 emissions to the atmosphere, only about 40 per cent (±15 per cent) of the emitted molecules will have been sequestered. After a thousand years about 75 per cent (±10%) will have been sequestered, and the remainder will gradually be removed over the ensuing tens of thousands of years.[11] Likewise, emission reductions take decades or centuries to lead to a reduction in the global concentration.

The CO_2 level as recorded at the Mauna Loa observatory in Hawaii is generally used as the representative global average concentration.[12] The concentration was about 315 parts per million (ppm) at the start of the record in 1958 and is now about 400 ppm, a 27 per cent increase. The record is subject to natural monthly fluctuations of about 0.5–2.0 ppm due to plant growth and decay, superimposed on an upward trend of about 1.5 ppm per year. If the entire increase is due to net anthropogenic emissions, in very approximate terms we can say that, on average, annual net global emissions of about 5 GtC translate into about a 1.5-ppm annual increase in the atmospheric stock of CO_2. Emissions would have to fall below the natural sequestration rate in order to eventually start reducing the atmospheric concentration. A reduction in global CO_2 emissions that still leaves positive net emissions would therefore not translate into a reduction in the global stock of atmospheric CO_2, only a slowing of the rate of increase. Under the 1997 Kyoto Protocol, which aimed to cap industrial nations' CO_2 emissions at five per cent below 1990 levels by the year 2012, atmospheric CO_2 levels would have continued to climb, only slightly more slowly, reaching their projected 2100 level in 2105 instead.[13] Had the non-industrialized countries also capped their emissions in 2010, the induced delay as of 2100 would only have been about 10 years. Similarly Lomborg[14] used the well-known MAGICC climate model and showed that full compliance with the Paris accord would yield a temperature reduction at the year 2100 of 0.05–0.17 C. This would mean hitting the baseline year 2100 temperature in around 2110 instead.[15]

Thus, unlike the case with conventional air contaminants, local actions yield extremely small and uncertain local benefits, and those only after a long time lag. The practice of referring to Canadian greenhouse gas initiatives as "combating climate change" or "taking action on climate" reflects a confused view of the scale of the issue. While this doesn't mean local emission reductions are worthless, it does point to the danger of overstating their impact.

Canada emitted 0.129 GtC in 2013,[16] up from 0.119 GtC in 1990. Thus Canada emits about 1.3 per cent of total global CO_2 emissions. Policy discussions in Canada, at least since the days of the Kyoto Protocol, have looked at the costs of reducing our total national emissions by some 10 to 30 per cent depending on the base year. At present this would amount to a reduction of about

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11 IPCC, *Climate*, 472–473.

12 These data are available online at ftp://aftp.cmdl.noaa.gov/products/trends/co2/co2_mm_mlo.txt.

13 T.M.L. Wigley, "The Kyoto Protocol: CO2, CH4 and climate implications," *Geophysical Research Letters* 25, 13 (1998): 2285-2288.

14 Bjorn Lomborg, "Impact of Current Climate Proposals," *Global Policy* 7, 1 (2016): 109-118. Available at http://onlinelibrary.wiley.com/doi/10.1111/1758-5899.12295/full.

15 ibid.

16 Boden et al., *Global*. These figures include emissions from fossil fuels, flaring and cement manufacture. Estimates for Canada are available at https://www.ec.gc.ca/ges-ghg/default.asp?lang=En&n=662F9C56-1 (accessed July 26, 2016). Note that they include all GHGs, including methane and other trace gases, and their estimates are in CO_2–equivalent rather than carbon-equivalent so they do not correspond exactly to the CDIAC numbers used here. Environment Canada estimates that total national GHG emissions (including CO_2) did not rise between 2013 and 2014.

0.01 to 0.03 GtC, which, if achieved, would eventually reduce the rate of increase in the global CO_2 concentration by about 0.01 ppm per year,[17] orders of magnitude smaller than the natural monthly fluctuations in the global record, and hence on a scale that for all practical purposes would have no discernable global effects. Complete cessation of all Canadian CO_2 emissions would reduce the global concentration by only about 3 ppm over the next 100 years.

This does not imply that Canada should do nothing, however. One of the advantages of approaching the issue as a pricing problem is that the scale question ceases to be an impediment to action. If the global social cost of a tonne of CO_2 is, say, \$20, then that is the price each emitter should pay, regardless of how large or small Canada's role is. By contrast, an attempt to justify a costly reduction in the quantity of Canadian CO_2 emissions based on the expected global climate impact will inevitably fall apart once the scale question is raised.

2. ECONOMICS OF CARBON PRICING

2.1 The Basic Rationale

The dollar value of the external costs of CO_2 emissions is commonly referred to as the social cost of carbon (SCC), which is shorthand for the marginal social damages of another tonne of CO_2 emissions added up across all years in which the CO_2 remains in the air. Computing a credible estimate of the SCC is a non-trivial challenge and the results span a wide range based on variations in only a few modelling assumptions (see Section 5). Notwithstanding these problems, economic theory has a great deal to say about the logic of carbon pricing and the optimal design of policies. A few basic points can be gleaned from the simple diagram shown in Figure 1. The marginal damages (*MD*) curve and the marginal abatement cost (*MAC*) curve characterize the economics of the externality problem in a manner analogous to, respectively, a supply-and-demand curve. They are interpreted as follows. [18]

Both lines are drawn on a graph that shows the quantity of emissions on the horizontal axis and a dollar amount per unit of emissions on the vertical axis. The *MD* curve (Figure 1) is a line that shows, at each point on the horizontal (emissions) axis, the marginal cost to society of increasing emissions by one tonne. Or, reading from right to left, it can be interpreted as the marginal benefit to society of emissions going down (referred to as abatement) by one unit.

The *MAC* curve is a downward-sloping line that meets the horizontal axis at the point E_0. At every point along the *MAC*, the height indicates the marginal cost to society of restricting the activities that generate emissions by enough to reduce emissions one more unit (if reading from right to left) or the marginal benefit to society of allowing a small increase in emissions (if reading from left to right). At E_0, the marginal benefit of the emitting activities is zero, so this is the level we associate with unregulated emissions.

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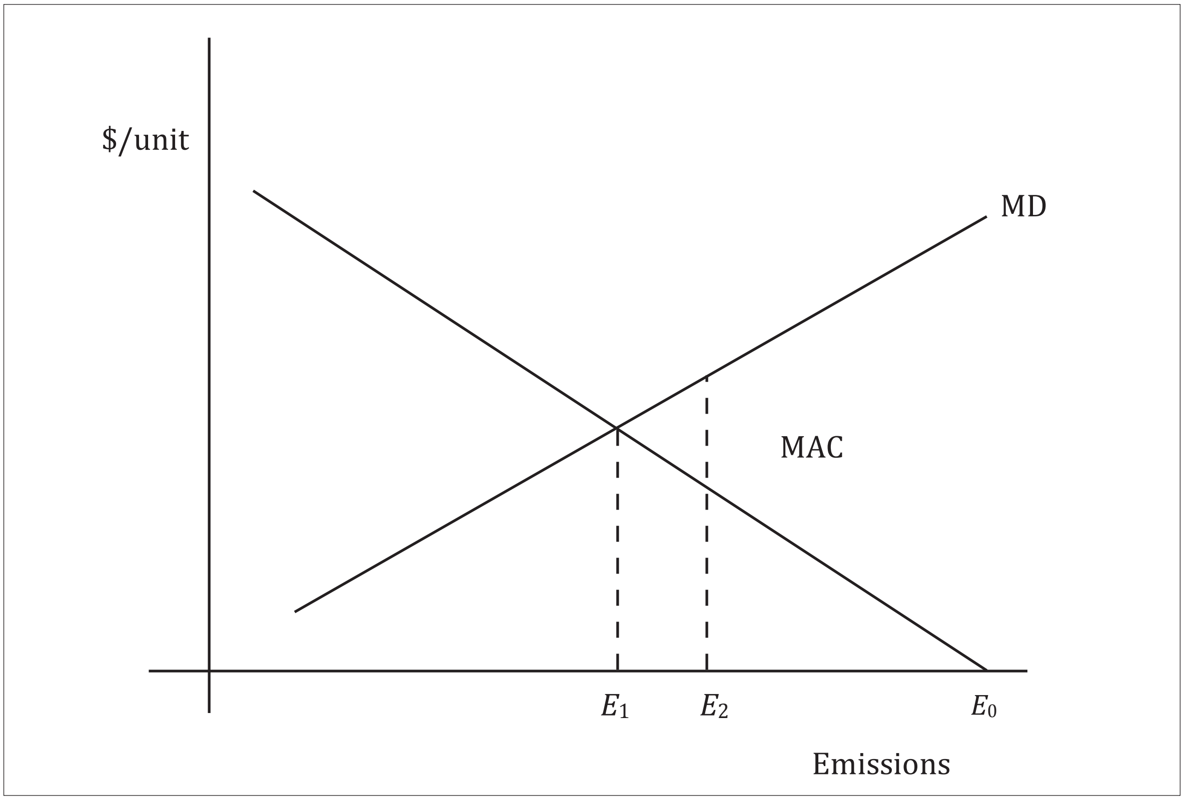
[17] If 5 GtC net emissions yields +1.5 ppm, then 0.01 GtC yields +0.003 ppm and 0.03 GtC yields +0.009 ppm.

[18] The points outlined here are explained in detail in any standard environmental-economics textbook, such as Barry C. Field and Nancy Olewiler, *Environmental Economics* (Toronto: McGraw-Hill, 2015), Chapter 5; and Ross R. McKitrick, *Economic Analysis of Environmental Policy* (Toronto: University of Toronto Press, 2010).

FIGURE 1 THE STANDARD MODEL OF OPTIMAL POLLUTION EMISSIONS



Over an interval, say from E_1 to E_2, the area under the *MAC* indicates the total cost of reducing emissions by that amount, or equivalently, the total benefit (to society) of the activity that results in that increase in emissions. The area under the *MD* line indicates the total damage from the increase, or alternatively, the total benefit from reducing emissions by the same amount. Achieving an optimal level of emissions control requires marginal damages to equal marginal abatement costs. In Figure 1 this occurs at E_1.

At emission levels above E_1, the policy is too lax. But note that there is a region from zero up to E_1 where policy is too stringent: in other words some of the emission reductions cost more than they are worth. Even if CO_2 causes environmental damages, it does not imply the optimal emissions level is zero. When people speak about the need to "decarbonize" the economy, or drive CO_2 emissions to zero, they are making extreme assumptions about costs and benefits that would be difficult to justify empirically.

Note that there is a price associated with the optimal emissions level E_1 in Figure 1. This is the optimal carbon-tax rate (though an important modification to this concept will be explained in Section 3).

The most efficient distribution of abatement responsibilities among a large group of emitters equates the marginal abatement costs of each one. This is called the equimarginal criterion. A policy that consists solely of a uniform carbon tax will yield a distribution of abatement activity that satisfies this condition, because each emitter will reduce emissions to the point where further reductions cost more than paying the tax. The government doesn't need to know what each emitter's best abatement options are; instead, the price instrument will give everyone an incentive to figure those out for themselves.

A quantity instrument for pricing could consist of a set of tradable permits, each one allowing the holder to release a tonne of emissions. As long as holders can freely trade their permits with each other, the outcome will also satisfy the equimarginal criterion. Firms trade to a point where the price they will pay for permits equals their MAC. If the quantity of permits is selected so that the permit price after trading equals marginal damages, then this system can also provide an optimal outcome.

These instruments look equivalent in a simple model that ignores the rest of the economy and assumes away uncertainty. In real-world settings they can have very different economic effects, especially if the permits are freely given away rather than auctioned, as will be explained in Section 4.

Standard assertions about the efficiency of carbon taxes assume the absence of pre-existing command-and-control CO_2 emission regulations. This was a reasonable assumption for Canada 20 years ago but it is not today. In the presence of inefficient pre-existing regulations, a carbon tax is not guaranteed to improve efficiency and may in fact worsen the distortions of the regulatory system. In the Canadian context, major emitting sectors (including power generation and transportation) are already subject to regulatory restrictions that preclude efficiency even in the presence of an emissions tax. Therefore, all the analysis in this report assumes that, if command-and-control regulations on CO_2 already exist, they need to be removed prior to implementing the carbon-pricing mechanism. A policy implementation scheme that leaves distorting regulations in place and simply adds a tax or tradable permits system on top has no claim to being economically rational or efficient.

While tax, permit and regulatory policies can all be constructed to yield the same reduction in emissions, from the point of view of individual firms, emission taxes may be quite a bit costlier because firms have to pay the tax bill on what they continue to emit. (This is also the case if permits are auctioned by the government.) From society's point of view, the tax is just a transfer from one place to another, so it is not a net social cost. But individual firms will certainly perceive it as such, unless the funds are used in some way that benefits them.

2.2 A Subtle Misunderstanding About Carbon Pricing

The primary objective of carbon pricing is to price carbon emissions. This might seem an obvious point, but it is helpful nonetheless to emphasize it. Once the price is set, it is up to the market to determine the response on the quantity axis. If an optimal carbon tax is introduced and replaces distorting command-and-control regulations, the end result may be an increase in emissions, but that would nevertheless be consistent with the policy being economically efficient and environmentally optimal. A recent report from the Eco-Fiscal Commission begins: "The primary objective of carbon pricing is to reduce greenhouse gas (GHG) emissions."[19] This statement is not quite correct: the primary objective is to make polluters pay, while giving them the freedom to decide how to respond to the tax. While the response will typically involve emission reductions, if the carbon price replaces a pre-existing command-and-control policy, the net effect may be an increase in emissions. Also, if the price change is small and the elasticity is low, the market quantity may barely change in response to the price. In this case it is sometimes asserted that carbon taxes "don't work" if emissions don't fall enough in response. But, once again, the point of the tax is to hit a price target, not a quantity target. If the price is

[19] Eco-Fiscal Commission, "Choose Wisely" (2016), 1, http://ecofiscal.ca/reports/choose-wisely-options-trade-offs-recycling-carbon-pricing-revenues.

being paid, the tax "works." If emissions don't fall by much, that only indicates the market for emissions is inelastic.

2.3 The Shape of the MD and MAC Curves

The first step in moving from theory to application is to consider whether it is possible to develop empirical versions of the *MD* and *MAC* curves. The numbers on the horizontal axis simply correspond to the range of Canadian CO_2 emissions. Canada's emissions peaked in 2007 at 153 megatonnes carbon equivalent (MtC) and have been falling since then.[20] Since then, Canadian emissions have been partly controlled through a patchwork of regulations. So we could approximately label the point $\bar{E}$ as 150 MtC.

We also have enough information to make two other points.

1. The *MD* curve for Canada must be flat, not upward-sloping as in Figure 1. Referring to the discussion in Section 1.2, it is the global concentration of CO_2 that affects welfare, not the emissions themselves. The marginal effect of a tonne of emissions depends on the current concentration of CO_2. Since Canada is so small, our emissions in any one year cannot change the global concentration (even over a century our total emissions would have only a very small effect). Therefore the first unit of our emissions in any one year must have the same marginal effect on welfare as the last unit, because the atmospheric concentration will remain the same over the whole range of emissions. This implies the *MD* line is flat. This reasoning applies to Canada's emissions, but would not change much when considering annual global emissions, due to the scale involved. As the global CO_2 concentration increases, this will shift up the intercept of the *MD* line but will not change the slope.
2. The *MAC* curve is likely steep, although since the *MD* curve is flat we don't need to assume this in order to implement an optimal policy. Fuel-demand elasticities tend to be small, which means it takes large price increases to induce reductions in consumption.[21] This likely translates into an inelastic, or steep, *MAC*. However, the more important point is that once we know the *MD* is flat, it does not matter whether the *MAC* is steep or not: as will be shown below, carbon pricing can be implemented in such a way as to yield optimal CO_2 emissions control either way.

Putting these points together yields Figure 2. Note that we do not yet have enough information to put numbers on the vertical axis, nor do we yet have enough information to estimate the optimum, which is labeled E^*. But theory and empirical work will allow us to fill in these gaps further.

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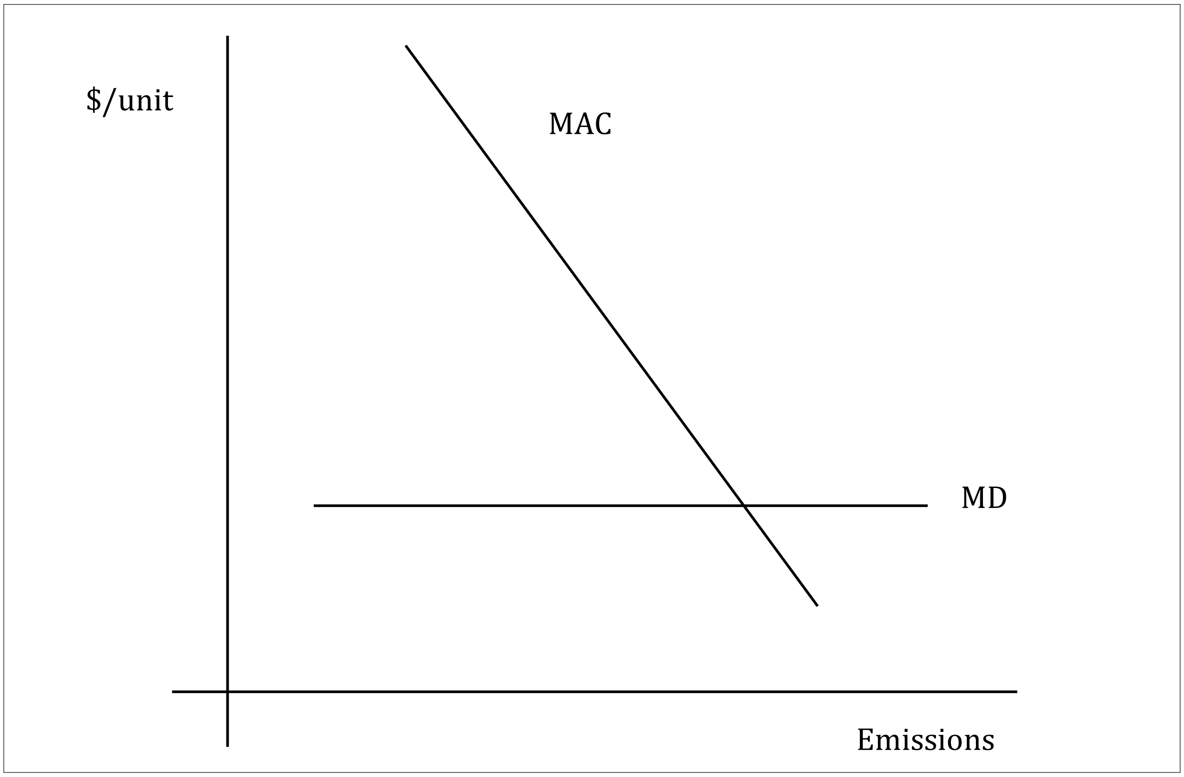
[20] Boden et al., *Global*.

[21] See Havranek, Tomas, Irsova Zuzana and Karel Janda (2011) "Demand for Gasoline is More Price-Inelastic than Commonly Thought." Energy Economics doi:10.1016/j.eneco.2011.09.003. and R. McKitrick (2012) "The High Price of Low Emissions: Benefits and Costs of GHG Abatement in the Transportation Sector" Ottawa: MacDonald-Laurier Institute, available online at macdonaldlaurier.ca for surveys related to motor fuels.

FIGURE 2 A POSSIBLE REPRESENTATION FOR THE CASE OF CO_2 EMISSIONS



3. MACROECONOMIC ANALYSIS OF CARBON-TAX INTERACTIONS

A policy to restrict CO_2 emissions (regardless of the instrument) generates chain reactions throughout the larger economy. If the policy raises revenue for the government, we need to decide what to do with the revenue. It has long been asserted in environmental economics that the new revenue should not be used to subsidize goods that are substitutes for the one generating the emissions.[22] This is at odds with the popular but misguided idea[23] that carbon tax revenues should be used to subsidize "green goods" or abatement technology. The logic of carbon pricing is that it induces the market to identify and implement the cheapest abatement options, and reject the rest. Using the revenues to subsidize the rejected ones would defeat the purpose of the policy.

Since a carbon tax, like any tax, causes deadweight losses,[24] the best option for recycling the revenues is to reduce other tax rates that have equivalent or larger deadweight losses at the margin. It is not always possible to maintain revenue neutrality and guarantee reductions in other tax rates. Introducing an emission tax implies increased costs and reduced economic

22 William Baumol and Wallace Oates, *The Theory of Environmental Policy* (Cambridge: Cambridge University Press, 1988), Chapter 4; A. Lans Bovenberg and Lawrence H. Goulder, "Optimal Environmental Taxation in the Presence of Other Taxes: General-Equilibrium Analyses," *American Economic Review* 86, 4 (1996): 985-1000.

23 For an example see P.J. Partington and Vickey Sharpe, "Using Carbon Pricing Revenues to Accelerate the Transition to a Low-Carbon Economy," in *Revenue Recycling: Six Position Papers on the Options for Recycling Carbon Pricing Revenue* (Eco-Fiscal Commission, April 2016), 43-64, http://ecofiscal.ca/wp-content/uploads/2016/04/Ecofiscal-Commission-Position-Papers-Options-Recycling-Carbon-Pricing-Revenue-April-6-2016.pdf.

24 A "deadweight loss," also called an "excess burden," is a cost to the economy from implementing a tax, over and above the amount raised by the government.

activity overall, which means that the rest of the tax base will shrink slightly. Offsetting this loss are the revenue gains from the new tax. Depending on which effect is larger, government net revenues may go down. In that case, revenue-neutrality may require other taxes to be increased, rather than decreased.

Even if overall net tax revenues go up, the increased production costs and decreased real wages elsewhere in the economy change the deadweight losses associated with pre-existing taxes, and this needs to be taken into account. When a tax rate is raised, some existing economic activity is cancelled, but not all. If there is a 30 per cent deadweight loss from an existing tax, that means $1.30 in economic welfare was lost in order to provide the last dollar of tax revenue. In this case we would call $1.30 the marginal cost of public funds (MCPF). Estimates of the MCPF vary widely depending on the type of tax,[25] with Canadian examples spanning 1.11 to over 40. For example, provincial personal income taxes in Canada have estimated MCPF rates ranging from 1.41 (Alberta) to 6.76 (Ontario).[26]

The MCPF is an important parameter in the analysis of carbon taxes because it changes the definition of the optimal price of emissions. In an important analysis published 40 years ago, Agnar Sandmo showed that, in a general-equilibrium setting, the optimal tax rate on emissions is not simply *MD*, as in the partial-equilibrium case, instead it is *MD/MCPF*.[27] In an economy with no other taxes, the *MCPF* equals one, since there is no deadweight loss associated with the very first dollar of tax revenue, so the optimal tax would equal *MD* as shown in Figure 1. But in any normal economy with pre-existing taxes, the optimal carbon tax rate needs to be deflated by the magnitude of the *MCPF*.[28] For this reason, even though CO_2 is a global pollutant, an optimal carbon tax should not be uniform across jurisdictions, but should be lower in economies that have relatively more distortionary tax systems. For Canada, a conservative estimate of the average provincial *MCPF* is 2.0,[29] meaning the optimal carbon tax should be about half of the estimated social cost of carbon.

4. TAXES OR TRADABLE PERMITS?

4.1 Scarcity Rents

By restricting emissions, the government forces firms to operate where they would be willing to pay a positive amount for the right to emit more. The total size of a market for tradable permits is the price times the quantity of permits issued by the regulator. So if the government issues 100 MtC worth of permits and they trade for $25 each, the permits market is worth $25 x 100,000,000 = $2.5 billion. The $2.5 billion is a *scarcity rent*, namely a pool of money created

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25 See survey in Lint Barrage, "Optimal Dynamic Carbon Taxes in a Climate-Economy Model with Distortionary Fiscal Policy" (2014), http://www.webmeets.com/files/papers/EAERE/2013/1261/Barrage_Lint_JMP_12_01_2012.pdf.

26 Ergete Ferede and Bev Dahlby, "The Costliest Tax of All: Raising Revenue Through Corporate Tax Hikes can be Counter-Productive for the Provinces," University of Calgary School of Public Policy Research Paper 9, 11 (March 2016).

27 Agnar Sandmo, "Optimal taxation in the presence of externalities," *Swedish Journal of Economics* 77, 1 (1975): 86–98.

28 The actual Sandmo formula is more complex, but the version presented here applies after a simplifying assumption of setting all cross-price elasticities to zero. A detailed explanation of the Sandmo model, and the related literature on the theory of emission taxes, is in McKitrick, *Economic*, Chapter 8. Also see Bovenberg and Goulder, "Optimal," and Barrage, "Optimal," for alternative derivations.

29 Ferede and Dahlby, "The Costliest," Table 2, shows provincial *MCPF* rates: B.C. 2.86, Alberta 1.41, Saskatchewan 2.38, Manitoba 2.42, Ontario 6.76, Quebec 3.05, New Brunswick 1.91, P.E.I. 2.80 and Newfoundland 2.16. Nova Scotia could not be calculated because an increase in the tax rate lowers overall revenue.

by imposing an artificial scarcity on something that was otherwise freely available. It is exactly akin to the value of dairy quota under milk-marketing-board plans, and in fact, such systems when applied to pollution control are usually called tradable quotas. Another name for this system is "cap and trade." The money comes from several places. Consumers are now paying higher prices, owners are getting a lower rate of return (and in some cases no return at all if the firm exits the industry) and workers are getting lower real wages. The incidence of these costs will depend on the various market elasticities. The money accrues to the firms when their free quotas are capitalized into their equity.[30] Consequently, firms subject to tradable quota systems can come out ahead financially, as did the first generation of dairy farmers subject to supply management.

Emission-reduction policies always create scarcity rents, regardless of whether the policy targets quantity or price.[31] The way that these rents are distributed has a very large effect on the overall macroeconomic costs of a policy. Economic modelling has generally found that the smallest macroeconomic costs occur when the rents are fully captured by the government and used to reduce the most distorting taxes in the economy. The costs go up when the revenues are used for purposes that are less valuable at the margin. Lump-sum rebates, for instance, do not reduce the marginal excess burden of the tax system, nor does giving away permits free to emitters, so these options are costlier overall.[32]

Parry, Williams and Goulder[33] found that for Kyoto-level emission cuts in the U.S., by not funding offsetting tax reductions, a tradable quota system would impose macroeconomic costs at least double those of a carbon tax. Model simulations of the U.S. economy by Bovenberg and Goulder,[34] that included taxes on intermediate goods, showed that the marginal welfare cost of achieving an eight per cent reduction in emissions would be about US$25 per American ton when revenues are returned through cuts in personal income taxes, but about US$75 per ton when revenues are returned lump-sum to households (which would correspond in the model to free allocation of tradable permits).

4.2 Minimizing the Costs of Mistakes

Uncertainty affects the choice between regulating prices versus quantities (in other words, whether to impose a carbon tax or a tradable permits system). I will explain this using a well-known analysis originally offered by Martin Weitzman.[35] Suppose we do not know where the *MAC* curve is or what it looks like, but we have information that tells us that the *MD* line is very flat or very steep. Looking at Figure 3, the top-left graph is the flat case and the top-right graph is the steep case. In the flat case, since we do not know where the *MAC* line is, we

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30 Gilbert E. Metcalfe, "Designing a Carbon Tax to Reduce U.S. Greenhouse Gas Emissions," *Review of Environmental Economics and Policy* 3, 1 (Winter 2009): 63–83.

31 They are also created when command-and-control is used. In this case they are even larger in magnitude because of the inefficient distribution of abatement requirements. But their value to firms is neutralized because they are, in effect, non-tradable. Consumers still incur the full cost of the scarcity rents, but they may accrue to no one.

32 Rents can also be lost under emission taxes if certain sectors are exempted or no-charge thresholds are allowed.

33 Ian Parry, Roberton C. Williams III and Lawrence H. Goulder, "When Can Carbon Abatement Policies Increase Welfare? The Fundamental Role of Distorted Factor Markets," *Journal of Environmental Economics and Management* 37 (1999): 52–84.

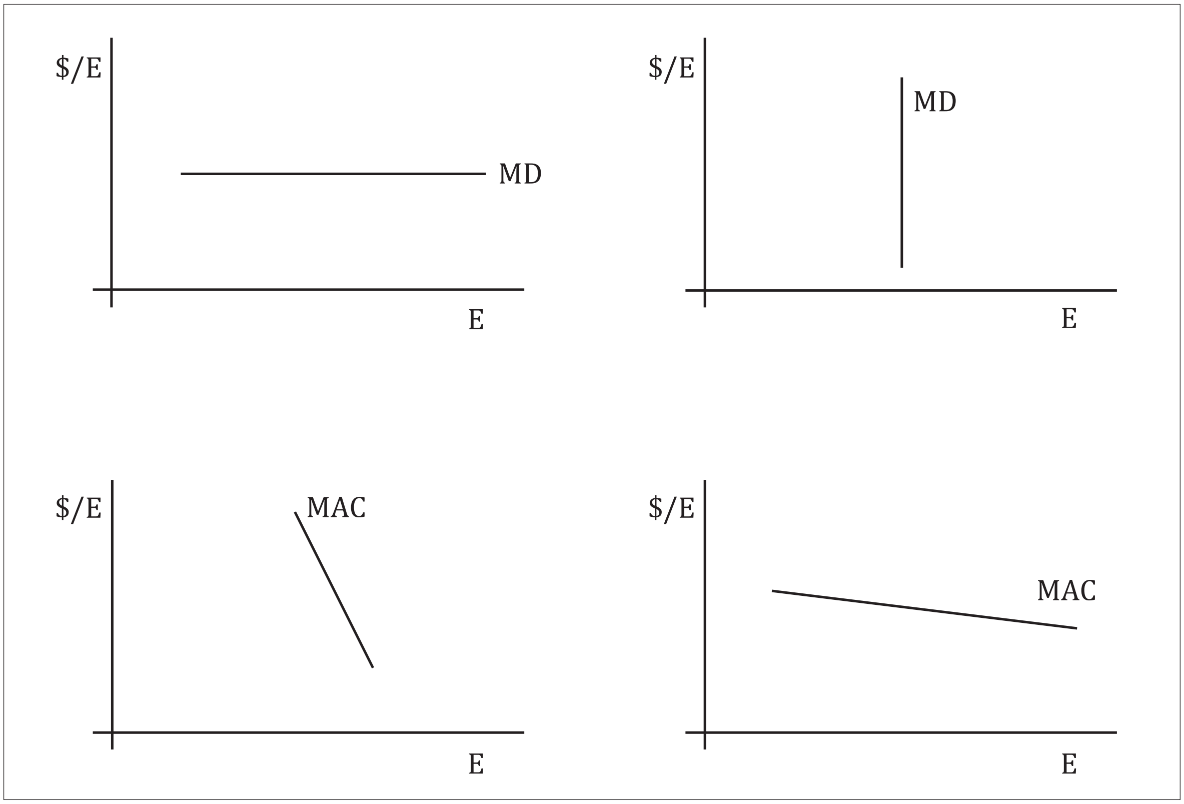
34 Bovenberg and Goulder, "Optimal." For a recent review of the modelling work on interactions between carbon taxes and the rest of the tax system see Lawrence H. Goulder, "Climate Change Policy's Interactions with the Tax System," *Energy Economics* 40 (2013), http://dx.doi.org/10.1016/j.eneco.2013.09.017.

35 Martin Weitzman, "Prices vs. Quantities," *The Review of Economic Studies* 41, 4 (1974): 477-91.

don't know what the optimal emissions quantity will be. But if we know what the numbers are on the vertical axis, we can tell pretty closely what the optimal price will be, even without knowing where the *MAC* is, since the *MD* line is flat. So in this case it is better to choose a price instrument. In the steep case, we don't know what the optimal price will be since it could be anywhere up the *MD* line, but if we know what the numbers on the horizontal axis are, we know pretty closely what the optimal quantity will be. So it is better to choose a quantity instrument in this case.

The bottom-left diagram illustrates a case in which we do not know where the *MD* line is but we know the approximate shape of the *MAC*. The steep case is on the left and the flat case is on the right. If the *MAC* is steep, we could make a wide range of guesses about the optimal price and it will always translate into a quantity lying in a very narrow range around what will have to be the optimum, regardless of where the *MD* is. So in this case we are better off picking the price we want. In the flat case, we could guess anywhere on the quantity axis and the resulting price will be constrained to be near the optimum. So we are better off to pick a quantity.

FIGURE 3 DIFFERENT CASES FOR UNDERSTANDING THE EFFECTS OF UNCERTAINTY



These considerations can then be combined to see if the shapes of the lines both reinforce the same judgment. In the CO_2 case as drawn in Figure 2, we have a flat *MD* and a steep *MAC*. Both features indicate a price instrument is preferred, a conclusion long shared among economists who have looked at the question.[36] Pizer[37] ran simulations on the U.S. economy of

[36] H.D. Jacoby and A.D. Ellerman, "The Safety Valve and Climate Policy," *Energy Policy* 32 (2004): 481–91; Ian W.H. Parry, "Fiscal Interactions and the Case for Carbon Taxes over Grandfathered Carbon Permits," Resources for the Future Working Paper DP 03-46 (Washington, D.C., 2003).

[37] William A. Pizer, "Prices vs. Quantities Revisited: The Case of Climate Change," Resources for the Future Discussion Paper 98-02 (1997).

the costs of uncertainty and showed that the expected welfare losses from picking a quantity of CO_2 would be about five times larger than those from picking a price.

Therefore, in an either/or choice, a carbon tax is a better option than tradable permits. The uncertainty problem can also be handled using a so-called hybrid instrument.[38] In this case a certain quantity of tradable permits is issued (either auctioned or given away), but at the same time the government announces a “safety-valve” price whereby a firm can choose to pay a tax in lieu of holding permits. If the market price for permits rises above the tax rate, no one will buy permits and they will pay the tax instead. So this effectively caps the price, instead allowing the quantity to increase in response to a price surge. Imposing a safety-valve price requires the government potentially to give up the ability to guarantee a quantity of emissions.

Since CO_2 is a polar case with a nearly flat *MD* there is no efficiency gain associated with using the hybrid instrument. The main potential advantage would be a practical one, namely if a policy-maker has an independent, non-economic reason for wanting to implement tradable permits, but doesn’t want to risk very high compliance costs.

5. COMPUTATION OF MARGINAL DAMAGES AND THE SOCIAL COST OF CARBON

5.1 GCMs and IAMs

Two types of models are used for the computation of marginal damages: general circulation models (GCMs), which represent the climate system in detail, and integrated assessment models (IAMs), which combine very stylized representations of both the climate and the economy.[39] IAMs take CO_2-emission scenarios as inputs and compute changes to the atmospheric stock of CO_2 and related climatic variables including temperature changes, which in turn lead to regional economic changes.[40] They then compute the optimal price to charge for additional CO_2 emissions, which is the basis for the SCC. The best-known IAMs are DICE (Dynamic Integrated Climate and Economy),[41] FUND (Climate Framework for Uncertainty, Negotiation and Distribution)[42] and PAGE (Policy Analysis of the Greenhouse Effect)[43].

In an IAM, economic activity is modelled by assuming there is a single decision-maker with perfect foresight who plans the optimal mix between savings and spending in order to balance

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38 The hybrid approach was first proposed by Marc J. Roberts and Michael Spence, “Effluent Charges and Licenses Under Uncertainty,” *Journal of Public Economics* 5 (1976): 193-208. See Jacoby and Ellerman, “The Safety,” for a discussion specifically related to climate policy.

39 Many early estimates of the total costs of global warming combined estimates of effects in specific regions or sectors worldwide derived from an eclectic mix of statistical and descriptive methods. These eventually contributed to the calibration of damage functions in IAMs. See Tol, “The Economic,” 29-51.

40 D. van Vuuren et al., “How well do integrated assessment models simulate climate change?” *Climatic Change* 104, 2 (2011): 255–285, http://www.pbl.nl/en/publications/2009/How-well-do-integrated-assessment-models-simulate-climate-change_.

41 W. Nordhaus, *A Question of Balance: Weighing the Options on Global Warming Policies* (New Haven, Conn.: Yale University Press, 2008).

42 R. Tol, “Estimates of the damage costs of climate change. Part I: benchmark estimates,” *Environmental and Resource Economics* 21 (2002): 47-73; R. Tol, “Estimates of the damage costs of climate change. Part II: dynamic estimates,” *Environmental and Resource Economics* 21 (2002): 135-160.

43 C. Hope, “Optimal carbon emissions and the social cost of carbon under uncertainty,” *The Integrated Assessment Journal* 8, 1 (2008): 107-122.

the need for economic growth with the desire to enjoy consumption along the way.[44] This yields a certain quantity of energy consumption and CO_2 emissions each period. These change the atmospheric CO_2 concentration over time, which then determine the average temperature of the climate via a sensitivity parameter. Changes in temperature affect people, which in turn gives rise to economic benefits and costs. At present, IAMs do not represent pre-existing tax distortions, but Barrage[45] has shown that introducing them reduces the resulting optimal carbon tax rate by 10–30 per cent, in line with the above discussion on the MCPF.

The SCC is the discounted present value of annual marginal damages computed over the lifetime of the incremental CO_2 residency in the atmosphere. SCC estimates are computed by running the IAM forward in time with a baseline level of emissions, then increasing the emissions by a small amount in one period, running the model forward once again, computing the differences in welfare each period, then discounting them back to the present. This requires assumptions about how to represent countless physical and economic processes. Tol[46] reported on a 2009 survey of over 230 SCC estimates that begin below zero and go up to over $1,000 per tonne, and there have been more since then. The U.S. government's Interagency Working Group[47] reported a range of marginal-damage estimates spanning -US$22 to US$727 per tonne of CO_2 under a three per cent discount rate. SCC variations largely arise from different treatments of two key parameters: the discount rate and climate sensitivity.

A typical outcome in an IAM model is a policy "ramp" in which a carbon tax starts low and rises over time. The recent literature on the "green paradox" is based on the possibility that such a policy could accelerate near-term extraction of fossil fuels (in anticipation of lower profits from delaying extraction), hence causing a paradoxical increase in current emissions and global warming.[48] While this outcome would still be optimal in economic terms, the fact that emissions get pulled forward in time and damages go up in the short run makes it seem worse than if the policy had not been implemented. Whether such an effect exists in reality or would be large enough to matter is not known.

5.2 Discounting

The long time scales involved in climate analysis imply that the choice of discount rate will have a very large influence on the results. A common approach in economic theory is to compute the discount rate using the so-called Ramsay formula, which decomposes it into two parts: the pure rate of consumer time preference (the rate at which individuals discount the value of consumption delayed by a year), plus a term representing the change in the marginal value of income. Over the long time scales involved in climate analysis there is an unavoidable amount of subjective judgment involved in selecting a discount rate, and readers of SCC analyses need to take careful note of the authors' assumptions.

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44 For a more detailed explanation see Alex L. Marten, "Transient Temperature Response Modeling in IAMs: The Effects of Over Simplification on the SCC," *Economics E-Journal* 5, 2011-18 (October 20, 2011), http://dx.doi.org/10.5018/economics-ejournal.ja.2011-18.

45 Barrage, "Optimal."

46 Tol, "The Economic."

47 United States. U.S. Interagency Working Group on Social Cost of Carbon (IWG), "Technical Support Document: Technical update of the social cost of carbon for regulatory impact analysis Under Executive Order 12866" (2013).

48 Frederick Van der Ploeg and Cees Withagen, "Is there really a green paradox?" *Journal of Environmental Economics and Management* 64 (2012): 342-363.

In Tol's 2009 survey, among studies that apply a one per cent discount rate, the median SCC is US$91, but if the discount rate is three per cent the median falls to US$36. The first report of the U.S. government's Interagency Working Group[49] used a range of discount rates; a three per cent discount rate yielded a 2020 SCC of US$37.79 in the DICE model. Another team showed that at five per cent, the SCC would fall to US$12.10, and at a seven per cent rate it would fall further to US$5.87.[50] The IWG also used the FUND model and computed a 2020 SCC of US$33 when applying a 2.5 per cent discount rate, US$19.33 using three per cent, US$2.54 using five per cent, and -US$0.37 using seven per cent.[51] In the IWG's 2013 update, which mainly involved some upward revisions to the damage functions, using the DICE and FUND models, it computed a 2020 SCC of US$29.40 at a three per cent discount rate.[52]

5.3 Climate Sensitivity

The representation of the climate is very simplified in an IAM, although it is calibrated to try and mimic more complex GCMs.[53] CO_2-induced changes are not always harmful. The FUND model, for instance, takes account of estimated improvements in agricultural and forest productivity at low levels of warming, as well as the potential growth of fertilization from higher CO_2 levels. As a result, the net effect of modest warming in some FUND simulations is globally positive.[54] Many other model simulations have found the effects of warming of around 1 C to be either zero or slightly positive.[55]

The important question for computing the SCC is thus not whether CO_2 emissions cause warming, but whether the effect is large enough to be harmful on balance. This hinges on climate sensitivity. The Intergovernmental Panel on Climate Change[56] defines equilibrium climate sensitivity (ECS) as the surface temperature change after CO_2 levels double in the atmosphere, after allowing the deep ocean to adjust, which may take more than a century. Traditionally, ECS has been simulated using GCMs by instantaneously doubling the level of CO_2 in the model atmosphere then allowing it to run until all processes are in a new equilibrium. Because GCMs exhibit chaotic behaviour, individual runs can vary widely, so the span of estimates tends to get compressed through averaging and modeller judgment. The earliest estimated range, the so-called Charney estimate from a 1979 report of the U.S. National Academy of Sciences, was 1.5 to 4.5 C with a best estimate of 3.0 C. This range predates

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49 United States. Interagency Working Group on Social Cost of Carbon (IWG), "Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866" (2010), http://www.whitehouse.gov/sites/default/files/omb/inforeg/for-agencies/Social-Cost-of-Carbon-for-RIA.pdf.

50 Kevin Dayaratna and David Kreutzer, "Loaded DICE: An EPA Model Not Ready for the Big Game," Heritage Foundation Center for Data Analysis Backgrounder No. 2860 (Washington, D.C.: Heritage Foundation, November 21, 2013), http://report.heritage.org/bg2860.

51 There is a large literature on long-term discounting, much of which emphasizes that, on large time scales, lower rates should apply, in particular due to uncertainty. In particular, taking into account the effect of large uncertainties on long time scales yields a declining, or hyperbolic, discount-rate path rather than a single, constant rate; See Richard Newell and William Pizer (2003) "Regulating Stock Externalities Under Uncertainty." *Journal of Environmental Economics and Management* 45:416—32.

52 IWG, "Technical." Model-specific results on page 19. Averaging in PAGE yields US$43.13.

53 Van Vuuren et al., "How well."

54 Tol, "Estimates, Part I," 47-73; and "Estimates, Part II," 135-160.

55 Tol, "The Economic." See also "Editors Note: Correction to Richard S. Tol's 'The Economic Effects of Climate Change,'" *The Journal of Economic Perspectives* 29, 1 (Winter 2015): 217-219, concerning the compilation of estimates.

56 IPCC, *Climate*.

almost all modern climate-modelling work and its wideness reflected the paucity of knowledge available to the early researchers at the time.

In an IAM, the assumed ECS distribution strongly determines the resulting distribution of SCC values. Unfortunately, after 35 years of effort, the span of ECS estimates from climate models has not narrowed. In the IPCC Fifth Assessment Report of 2013 the reported range was, once again 1.5 to 4.5 C, and this time they did not even offer a best estimate.[57] IAMs use a skewed ECS distribution, with a minimum about 1.0 C, a median about 3.0 C and an upper tail typically well over 6.0 C.[58] For the official U.S. government SCC estimate, the U.S. Interagency Working Group (IWG) report[59] used an ECS distribution taken from a 2007 survey by Roe and Baker,[60] which has a median of 3.0 C, a fifth percentile of 1.72 C and a 95th percentile of 7.14 C. In its technical update of 2013,[61] the IWG did not revise this distribution, even though Roe himself[62] criticized its use as being inappropriate for IAMs because the upper tail only applies on time scales far too long to be relevant for SCC calculations.

In recent years, sufficiently detailed long-term climate data sets have become available to allow scientists to begin estimating ECS directly using empirical methods. Since 2012 at least 10 papers in peer-reviewed journals have used diverse statistical methods on up-to-date temperature data sets (including ocean heat content) in order to constrain the ECS to a distribution consistent with century-scale historical observations.[63] [64] This literature, the authors of which include many climate modellers and IPCC lead authors, has consistently yielded median ECS values at the bottom end of the range simulated in climate models. The median of recent empirical estimates has generally been between 1.5 and 2.0 C, with 95 per cent uncertainty bounds below the Roe-Baker average. The inconsistency between models and

57 See historical survey in N. Lewis and M. Crok, "Oversensitive: How the IPCC Buried Evidence Showing Good News about Global Warming," Report 13 (The Global Warming Policy Foundation, 2014), http://www.thegwpf.org/oversensitive-ipcc-hid-good-news-global-warming/.

58 An earlier version of FUND used a median of 2.5 C (van Vuuren et al., "How well"), but the newer version now contains a temperature-response function closer to DICE and PAGE. See Alex L. Marten, "Transient Temperature Response Modeling in IAMs: The Effects of Over Simplification on the SCC," *Economics E-Journal* 5, 2011-18 (October 20, 2011), http://dx.doi.org/10.5018/economics-ejournal.ja.2011-18.

59 IWG, "Social cost."

60 Gerard H. Roe and Marcia B. Baker, "Why Is Climate Sensitivity So Unpredictable?" *Science* 318, 5850 (October 26, 2007): 629–632.

61 IWG, "Technical."

62 Gerard H. Roe and Yoram Bauman, "Climate Sensitivity: Should the climate tail wag the policy dog?" *Climatic Change* 117, 4 (2013): 647–662.

63 M. Aldrin et al., "Bayesian estimation of climate sensitivity based on a simple climate model fitted to observations of hemispheric temperatures and global ocean heat content," *Environmetrics* 23 (2012): 253-271; M.J. Ring et al., "Causes of the Global Warming Observed since the 19th Century," *Atmospheric and Climate Sciences* 2 (2012): 401-415; S.E. Schwartz, "Determination of Earth's transient and equilibrium climate sensitivities from observations over the twentieth century: strong dependence on assumed forcing," *Surveys in Geophysics* 33, 3–4 (2012): 745–777; N. Lewis, "An objective Bayesian, improved approach for applying optimal fingerprint techniques to estimate climate sensitivity," *Journal of Climate* 26 (2013): 7414-7429; A. Otto et al., "Energy budget constraints on climate response," *Nature Geoscience* 6 (2013): 415–416; T. Masters, "Observational estimate of climate sensitivity from changes in the rate of ocean heat uptake and comparison to CMIP5 models," *Climate Dynamics* 42, 7 (2013); R.B. Skeie et al., "A lower and more constrained estimate of climate sensitivity using updated observations and detailed radiative forcing time series," *Earth System Dynamics* 5 (2014): 139–175; C. Loehle, "A minimal model for estimating climate sensitivity," *Ecological Modelling* 276 (2014): 80-84; D.J.A Johansson et al., "Equilibrium climate sensitivity in light of observations over the warming hiatus," *Nature Climate Change* (2015); N. Lewis and J.A. Curry, "The implications for climate sensitivity of AR5 forcing and heat uptake estimates," *Climate Dynamics* 45, 3 (2015).

64 There is a discussion of the earlier portion of this literature in IPCC, *Climate*, Section 10.8.2.1.

empirical results is attracting growing attention in the climatology literature.[65] It is also alluded to in the latest documentation for Nordhaus's DICE model[66] where it is cited as a reason for a slight downward revision in the ECS parameter.

For the most part, however, the inconsistency between empirical and model-simulated ECS estimates has been ignored in the economics literature. Dayaratna et al.[67] re-estimated the SCC values from DICE and FUND, substituting in the Lewis and Curry[68] empirical ECS values, which are conditioned on an empirical estimate of ocean-heat uptake efficiency. In the DICE[69] model, the Roe-Baker ECS distribution under a three per cent discount rate yields an average SCC value for 2020 of US$37.73 with a lower fifth percentile of US$16.76 and an upper 95th percentile of US$70.89. [70] Using the empirical ECS distribution instead, the average falls to US$19.52 with fifth- and 95th-percentile bounds of US$7.70 and US$46.94 respectively. In the FUND model, the average estimated SCC for 2020 falls 83 per cent from US$19.33 (fifth- and 95th-percentile bounds: -US$4.48, US$55.33) to US$3.33 (fifth- and 95th-percentile bounds: -US$14.66, US$28.64),[71] with about 40 per cent of the distribution now below zero.[72] Averaging the DICE and FUND models together and using the empirical ECS estimate yields a 2020 SCC estimate of US$11.43, with a lower fifth-percentile bound of -US$3.48 and an upper 95th-percentile bound of US$37.79.

To summarize, the social cost of carbon cannot be observed, it is computed using IAMs, which of necessity embed assumptions about many parameters. Two of these parameters, the discount rate and the equilibrium climate sensitivity, strongly influence the resulting SCC values. In the absence of empirical constraints on key parameters, there is a large arbitrary element in SCC calculation.[73]

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65 See for example J.R. Kummer and A.E. Dessler, "The impact of forcing efficacy on the equilibrium climate sensitivity," *Geophysical Research Letters* 41, 10 (2014).

66 See William Nordhaus and Paul Sztorc, *DICE 2013R: Introduction and User's Manual*, Second Edition (2013), 17-18, http://aida.wss.yale.edu/~nordhaus/homepage/documents/DICE_Manual_100413r1.pdf.

67 Kevin Dayaratna, Ross McKitrick and David Kreutzer, "Empirically-Constrained Climate Sensitivity and the Social Cost of Carbon," University of Guelph Department of Economics Discussion Paper 2016-08 (2016), https://ideas.repec.org/p/gue/guelph/2016-08.html.

68 Lewis and Curry, "The implications."

69 DICE does not take account of productivity gains in agriculture and forestry from higher CO_2 levels and warmer temperatures, so its SCC estimates are consistently higher than those from FUND. PAGE is slightly higher still due, in part, to stronger carbon-cycle feedbacks that slow down sequestration of CO_2 emissions.

70 The distributions are skewed so the confidence intervals are not symmetric around the mean.

71 The fifth- and 95th-percentile values are from Dayaratna (personal communication).

72 The U.S. National Academy of Sciences has an expert committee engaged in an ongoing review of the SCC issue in collaboration with the IWG. Unfortunately, in their interim report they, like the IWG, declined to modify the ECS parameter. Their reasoning was that since it is "only one input to the framework used to estimate the SCC, updating the ECS alone may not significantly improve the estimates." See The National Academies of Sciences, Engineering, and Medicine website, "Assessing Approaches to Updating the Social Cost of Carbon," http://sites.nationalacademies.org/DBASSE/BECS/CurrentProjects/DBASSE_167526. This reasoning is clearly flawed. Neither the NAS nor the IWG has any qualms about varying the discount rate in isolation, and while ECS is only one parameter, it is as influential as the discount rate, if not more so.

73 Robert Pindyck, "Climate Change Policy: What Do the Models Tell Us?" *Journal of Economic Literature* 51, 3 (2013) 860-872.

6. COMPUTATION OF MARGINAL ABATEMENT COSTS

6.1 MAC depends on the Policy

Unlike the MD curve, the MAC curve is affected by the form of the policy itself. The minimum MAC is obtained using carbon taxes or auctioned quotas. All other forms of policy raise the costs of reducing emissions, sometimes quite substantially.[74]

MACs for CO_2 abatement have been computed using a number of modelling methods. As mentioned above, conventional end-of-pipe abatement systems do not reduce the CO_2 emissions associated with each unit of fuel consumed. The only end-of-pipe abatement for CO_2 is carbon capture and storage, which at present is very costly and practical in only a few places due to the need for suitable geological formations. Beyond these, the only strategies to reduce CO_2 emissions are to switch from coal and oil to natural gas, which has less carbon per unit of energy, or to reduce fossil fuel consumption. In some cases this can happen at low costs. For instance, after the shale gas boom in the U.S., many utilities found it profitable to convert their power plants from coal to natural gas, which ended up saving them money even as their CO_2 emissions fell. But if an economy needs to reduce CO_2 emissions by cutting overall energy consumption, the MAC will likely be rather steep, and even large emission taxes may only yield modest CO_2 emission reductions.

6.2 CGE Versus Engineering Analysis

Computable general-equilibrium (CGE) models can be used to simulate the macroeconomic costs of CO_2-emission reductions. They are sometimes called “top down” models because they begin with descriptions at the macroeconomic level and then downscale to the sectoral level. CGE models assume that firms and consumers make optimal decisions, given the prices and technologies they face in the market. Therefore it is not possible in a CGE model to introduce a policy that forces firms to make decisions that increase their private profits, since they would have made those decisions already, although it is possible to introduce policies that benefit some firms at the expense of others. Likewise regulators cannot constrain households to make decisions that make them all privately better off, since it is assumed they would have made those decisions themselves already.

For instance, suppose the price of natural gas falls so that it becomes privately profitable for electricity generators to switch from coal to gas. At the same time, the government introduces a policy to require power plant CO_2 emissions to drop by more than the amount occasioned by the price-induced fuel switch. CGE analysis would focus on the cost of the additional emission reductions after utilities optimally adjust their fuel mix. The profits from the initial switch to gas would not be credited against the cost of the policy since the switch would have happened anyway even if the policy had not been implemented.

Other types of models, often ones that come from engineering-based analyses, are called “bottom up” since they begin with sector-specific detail and build their way up to the macro scale. Since they do not presuppose optimizing behaviour, they can have scenarios in which households and firms systematically make sub-optimal decisions that leave them privately worse off, and the government can introduce regulatory measures that force agents to

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[74] See Gloria E. Helfand, “Standards versus Standards: The Effects of Different Pollution Restrictions,” *The American Economic Review* 81, 3 (1991): 622–34; and discussion in Ross R. McKitrick, *Economic Analysis of Environmental Policy* (Toronto: University of Toronto Press, 2010), chapters 5 and 6.

undertake actions that make them better off. A well-known example of this is the McKinsey MAC curve.[75] In its study, McKinsey looked at the costs of reducing global CO_2 emissions to 35 per cent below 1990 levels, concluding that about one-third of the methods would have negative costs, or in other words, would be privately profitable for households and firms if only the government would force their adoption.

Economists have criticized this kind of analysis because it presupposes widespread incompetent decision-making by households and firms that can be rectified by the actions of a government planner who is himself or herself immune from making such errors. Gayer and Viscusi[76] review and critique the role such models are playing in the formation of current U.S. energy efficiency regulation. CGE models avoid this inconsistency by assuming agents optimize based on their private information about their own preferences, objectives and constraints. Therefore, any regulatory action that forces them to a decision other than the one they would privately have chosen must make them individually worse off, though it can make society better off if there are sufficient gains to public co-ordination. This implies that any so-called "negative cost options" cannot be counted against the costs of GHG abatement, because if they really existed they would already have been undertaken before the regulatory process got underway.

On the other hand, CGE models also rule out the possibility of persistent out-of-equilibrium conditions for the economy; so, for example, if one sector declines due to a policy change, all the workers and investors displaced from that sector end up going to another sector, albeit at a lower rate of earnings. For that reason, CGE cost estimates can sometimes be smaller than those from bottom-up models, if the latter permit unresolved unemployment of workers and capital to persist following a policy change.

6.3 Cost Estimates for Canada

Many of the Canadian studies on the costs of reducing CO_2 emissions were done in the 1990s for the purpose of analysing the cost of compliance with the Kyoto Protocol. Because of the magnitudes involved, most such estimates are expressed in percentage points of Gross Domestic Product (GDP).

A 1992 study for Finance Canada[77] used a CGE model to estimate the costs of meeting the "Rio" target: reducing CO_2 emissions to 1990 levels by 2000, which would have entailed a 12.5 per cent emissions cut. They estimated it would require a tax of $27.70 per tonne of CO_2, which would cost about 0.5 per cent of real GDP. Using a set of command-and-control regulations instead raised the costs to 0.8 per cent. They also found that the marginal cost of emission reductions is increasing, such that a target twice as stringent would cost two to three times more. As this was a static CGE model, it assumed the national capital stock is fixed, so losses over time due to reduced investment and capital outsourcing were not included.

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[75] McKinsey & Co., "Pathways to a Low-Carbon Economy" (2009). Downloaded from http://www.mckinsey.com/client_service/sustainability/latest_thinking/greenhouse_gas_abatement_cost_curves.

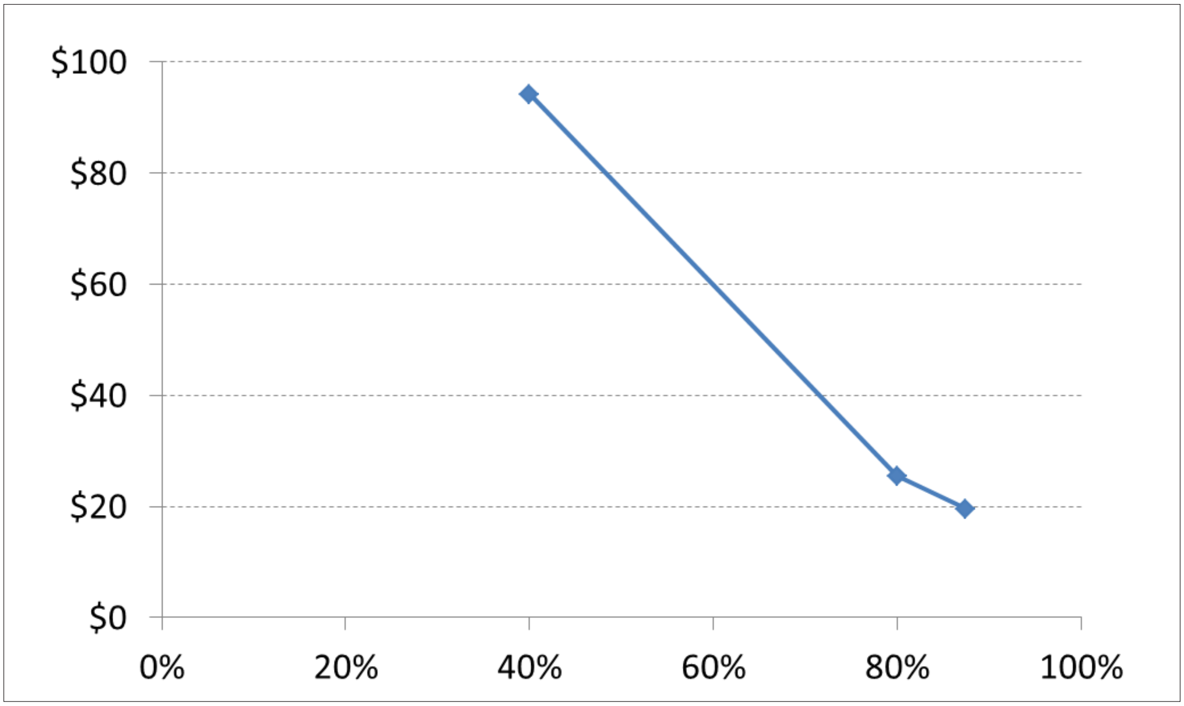
[76] Ted Gayer and V. Kip Viscusi, "Overriding consumer preferences with energy regulations," *Journal of Regulatory Economics* 43 (2013): 248–264.

[77] Louis Beauséjour, Gordon Lenjosek and Michael Smart, "An Environmental CGE Model of Canada and the United States," Department of Finance Working Paper 92-04 (Ottawa: Department of Finance, 1992).

A 2001 Industry Canada study[78] looked at a range of policy options to reduce Canadian emissions by 25 per cent. This was estimated to require a tax of $68.18 per tonne of CO_2, costing 1.1 per cent of real GDP. If exemptions were given to certain sectors while the overall target was held constant, the costs quickly rose. Exempting the non-energy-intensive sectors led to economic losses of 1.5–2.0 per cent, while exempting energy-intensive sectors and focusing policy elsewhere could cost up to 7.5 per cent of GDP. A key question is whether Canada acts unilaterally. To the extent our energy costs rise relative to those in the U.S., macroeconomic effects due to capital flight and deteriorating trade competitiveness increase. Hence, the shape of the MAC not only depends on the form of domestic policy, but also the degree of co-ordination with major trading partners.

An earlier study[79] presented results from simulations using carbon dioxide taxes with a variety of revenue-recycling options. In a static simulation (fixed capital) in which emissions were reduced by 12.5 per cent using a carbon tax with the proceeds allocated to personal income tax reductions, a tax of $19.51 per tonne of CO_2 was needed and resulted in a 0.3 per cent reduction in real consumption. For a 20 per cent cut in emissions, allowing investors to withdraw capital from the economy in response to the reduced rate of return, a carbon tax of $25.44 per tonne of CO_2 was needed, translating into a 2.0 per cent drop in real consumption. Finally, an emissions reduction of just under 60 per cent required a tax of $94.17 per tonne of CO_2 and caused a 17 per cent drop in real consumption. The resulting MAC is shown in Figure 4.

FIGURE 4 MARGINAL ABATEMENT COSTS FOR CANADA



Data from Ross R. McKitrick, "The Economic Consequences of Taxing Carbon Emissions in Canada," Report 5-55896 to Environment Canada, mimeo (1996). Horizontal axis: CO_2 emissions as a percentage of 1990 levels. Vertical axis: tax per tonne of CO_2 (1989 CDN$).

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78 Randy Wigle, "Sectoral Impacts of Kyoto Compliance," Industry Canada Working Paper No. 34 (Ottawa: Industry Canada, March 2001).

79 McKitrick, "The Economic."

Recently the Parliamentary Budget Office[80] presented an overview of CO_2-abatement challenges for Canada. It cited some earlier CGE analyses that put the cost of a 30 per cent emission reduction at between 1.0 and 3.0 per cent of real GDP, assuming the instrument is a carbon tax with some form of revenue recycling.

6.4 Optimal Either Way

With a flat MD curve the regulator does not need to know which MAC estimate is correct in order to hit the optimum. If the optimal emissions price is MD per unit, and the government simply imposes that charge (deflated by the MCPF) the market will drive emissions down to the optimal point. If the result is deep emission cuts that means the MAC looked more like the McKinsey graph. If the top-down analysis is correct, emissions will not fall much. Either way, the outcome will be optimal and firms will be operating at equimarginal levels. The policy-maker will be able to tell after the fact which MAC was correct by observing the response to the emissions tax. It won't be possible to determine the resulting emissions level ahead of time, but it will nonetheless be optimal.

6.5 Handling Dynamic Uncertainty

IAMs are very important tools for thinking through the dynamic carbon-pricing issue and weighing the influence of different assumptions. But for the purpose of forecasting climate and computing optimal tax rates, the arbitrary elements in IAM structure, and the wide range of resulting estimates, has led to pessimism about whether they actually reduce uncertainty.[81] Two previous authors[82] introduced learning into the IAM framework by supposing we can tweak the policy, observe the response of the climate, then use this information to refine the policy. The goal would be a situation in which the policy-maker has enough data to be able to draw a statistically significant distinction between the correct and incorrect policy. These studies showed that uncertainty about even one or two key parameters slows the learning time to at least several hundred years, meaning that we might never know what the right tax rule is.

McKitrick[83] presents an alternative approach akin to updating rules used in monetary policy. He notes that ECS is essentially a function relating past emissions to the climate state, and while its exact form may be unknown, the state itself is observable, and contains useful information. He presents a rule that ties the optimal tax to observed temperatures, essentially anchoring the tax to the climate state, and shows that such a tax must be highly correlated over time to the unobservable optimum. As with rule-based interest-rate policies, agents will not know the future levels, instead they have to act based on expectations. Those who expect rapid global warming, for instance, will expect the tax to increase rapidly, whereas those who expect little warming will expect it to remain relatively unchanged from its initial value. Both Hsu,[84]

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80 Philip Bagnoli, "Canada's Greenhouse Gas Emissions: Developments, Prospects and Reductions" (Ottawa: Parliamentary Budget Officer, 2016), http://www.pbo-dpb.gc.ca/web/default/files/Documents/Reports/2016/ClimateChange/PBO_Climate_Change_EN.pdf.

81 Pindyck, "Climate."

82 D. L. Kelly and C. D. Kolstad, "Bayesian learning, growth, and pollution," *Journal of Economic Dynamics and Control* 23, 4 (1999): 491-518; A. J. Leach, "The climate change learning curve," *Journal of Economic Dynamics and Control* 31, 5 (2007): 1728-1752.

83 Ross McKitrick, "State-Contingent Pricing as a Response to Uncertainty in Climate Policy" in *Handbook on Energy and Climate Change*, ed. Roger Fouquet (Cheltenham: Edward Elgar, 2013), 415-433.

84 Shi-Ling Hsu, "A Prediction Market for Climate Outcomes," *University of Colorado Law Review* 83 (2011): 179-256.

and McKitrick,[85] look at supplementing the tax with a futures market for permits defined so that each one exempts the holder from paying the tax on a tonne of CO_2 in the year indicated. In order to price such certificates, market participants would have to exploit all available information about the future path of the tax, and hence of the climate. It has been recently shown that such a market would yield unbiased climate forecasts, and would make more efficient use of all available information about the climate, the higher is the level of consensus on climate science.[86]

7. SUMMARY: A PRACTICAL STRATEGY FOR OPTIMAL CO_2-EMISSION PRICING

A policy-maker wanting to implement the optimal CO_2-control policies does not actually need to know what the MACs are in order to act. Enough information has been provided up to this point to allow any policy-maker to achieve an optimal implementation of CO_2-emission controls. The steps are as follows.

a) Regardless of policy, to achieve optimal implementation there is no avoiding the need to settle on an estimate of the social cost of carbon, so this should be done based on the best available information. Because the Canadian MD curve is horizontal (and the global one would be nearly so), the optimal instrument is a carbon tax, rather than tradable permits or quantity restrictions.

b) The carbon tax should be implemented *instead of*, not *on top of* other CO_2-emission policies in order to achieve economic efficiency. In other words, existing regulatory controls on CO_2 emissions need to be repealed and replaced by a carbon tax, otherwise the carbon tax will simply make the regulatory distortions worse, and will not introduce any new efficiency into the policy mix.

c) SCC estimates span a very wide range due to the influence of the discount rate. In view of the very long time scale involved, a discount rate of three per cent or less is reasonable.

d) The assumed value of climate sensitivity also strongly affects the SCC. Using the average of the three best-known IAMs, the U.S. government estimated an SCC of US$43 per tonne of CO_2 as of 2020.[87] However, in its 2013 update, the IWG did not take into account the empirical literature on climate sensitivity. Re-computation of the SCC using a recent empirical estimate causes the SCC to fall by 40–80 per cent depending on the model. The average of the FUND and DICE year-2020 tax rates applying a three per cent discount rate is US$11.43, and the fifth- and 95th-percentile bounds are -US$3.48 and US$37.79 respectively.[88]

e) The optimal carbon tax needs to be deflated by the estimated marginal cost of public funds to adjust for distortionary interactions with the rest of the tax system. Using an MCPF of 2.0 brings the tax rate to US$5.72. The worldwide range of carbon taxes spans about US$2

85 McKitrick, "State-Contingent."

86 Elmira Aliakbari, "Information Aggregation in a Prediction Market for Climate Outcomes" (PhD diss., University of Guelph, 2016).

87 IWG, "Technical."

88 Dayaratna, McKitrick and Kreutzer, "Empirically-Constrained." The percentile values are from Dayaratna (personal communication).

to US$170[89] so this would be on the low end, but not the lowest. Future revisions should take into account new information about climate sensitivity.

f) Whether emissions fall by much or not will depend on whether the MAC is steep or shallow. But the result will be economically and environmentally optimal either way. The policy-maker does not need to know in advance which is more likely in order to be assured that the outcome was the correct one, conditional on the chosen value of the SCC.

[89] World Bank, "Putting a Price on Carbon With a Tax," mimeo (2013), http://www.worldbank.org/content/dam/Worldbank/document/SDN/background-note_carbon-tax.pdf, accessed June 17, 2016.

About the Author

Ross McKitrick is a Professor of Economics at the University of Guelph, and Research Chair in Energy, Ecology and Prosperity at the Frontier Centre for Public Policy. He has published widely on the economics of pollution, climate change and public policy. His textbook, Economic Analysis of Environmental Policy, was published by the University of Toronto Press in 2010. His background in applied statistics has also led him to collaborative work across a wide range of topics in the physical sciences including paleoclimate reconstruction, malaria transmission, surface temperature measurement and climate model evaluation. Professor McKitrick has made many invited academic presentations around the world, and has testified before the U.S. Congress and committees of the Canadian House of Commons and Senate.

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