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On the Economics of a Carbon Tax for the United States

Gilbert E. Metcalf, Tufts University

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Gilbert E. Metcalf
Tufts University and NBER

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Abstract

Climate change is driven by a build-up of greenhouse gases (GHGs) in the atmosphere, predominantly the result of the world's consumption of fossil fuels. GHGs are a global pollution externality for which a global solution is required. I describe the role a domestic carbon tax could play in reducing U.S. emissions and compare and contrast to alternative approaches to reducing our GHG pollution. Carbon taxes have been implemented in twenty-seven jurisdictions around the world. I provide evidence on emission reductions and economic impacts of the British Columbia carbon tax, a broad-based carbon tax that has been in effect for over a decade now.

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I. Introduction

Climate change is a classic global pollution externality with billions of polluters creating damages for billions of people. Moreover, our continued use of fossil fuels and other greenhouse gas emitting activities creates damages that will affect future generations. This paper considers the role that a carbon tax could play in the United States as its contribution to reducing emissions. While climate change is a global problem and the United States has been surpassed by China as the world's largest emitter, I focus on domestic policy. A domestic carbon tax alone will not make a major dent in global emissions. But it is difficult to imagine other countries taking aggressive action to curb greenhouse gas emissions if the United States does not enact strong policy to reduce its emissions.

This paper argues that a carbon tax should be the central element of U.S. policies to reduce emissions. Putting a price on carbon pollution is a straightforward application of Pigouvian pollution pricing and a textbook response to the market failure arising from pollution. While a carbon tax is a necessary element in a cost-effective policy approach to pollution, it is not sufficient. Moving to a zero-carbon economy will require new inventions and production processes. Whether it is advanced battery storage, carbon capture and storage, or inexpensive, safe, and modular nuclear power, research and development (R&D) will be key to their successful development and diffusion. Information and new knowledge is a pure public good that is underprovided in a market economy.[1] The information market failure is a general market failure and not one specific to greenhouse gas emissions. But R&D is central to any solution to the greenhouse gas problem and directed R&D support can ensure emission reduction targets are met with lower carbon tax rates and the consequent economic costs of the tax, a point made by Acemoglu et al. (2012) and Acemoglu et al. (2016). These two market failures – pollution and the

[1] There are two issues here. First is the ability of private inventors to appropriate the benefits of their inventions. Patent protection is an imperfect policy tool for this, thereby deterring R&D. Second is the fact that even with the ability to fully appropriate the gains, the pure public goods nature of new ideas means that the social gains likely exceed the private gains.

pure public goods nature of R&D – should drive our choice of policy. In section VI, I discuss other policy needs to complement the carbon tax and energy-related R&D.

Section II of the paper briefly describes climate change and the damages from failing to act to reduce our carbon pollution. Section III compares and contrasts a carbon tax with alternative policy approaches. In section IV, I survey the use of carbon taxes around the world. In section V, I present some evidence on the economic impact of carbon taxes with a particular focus on the emissions and GDP impacts of British Columbia's carbon tax. Section VI presents some thoughts on policy design and section VII concludes.

II. Climate Change

Climate change is a catch-all term for the climate impacts arising from accumulations of greenhouse gases in the Earth's atmosphere. The most prominent greenhouse gas is carbon dioxide, accounting for three-quarters of global emissions. Methane is the second most prominent gas accounting for a further 16 percent of global emissions. Nitrous oxides (N_2O) and other gases account for the remaining 8 percent of greenhouse gas emissions. Carbon dioxide is a higher share of U.S. GHG emissions, accounting for 82 percent with methane accounting for 10 percent and nitrous oxides and other gases accounting for the remaining 8 percent.[2]

Focusing on sectors, 84 percent of U.S. greenhouse gas emissions are in the energy sector. Agriculture accounts for 9 percent, industrial processes and product use for 6 percent, and waste for 2 percent. Within energy, 94 percent of emissions are from carbon dioxide, of which 97 percent is associated with fossil fuel combustion. Breaking down energy-related fossil fuel combustion CO_2

[2] These data are for 2014 and are taken from WRI's CAIT Climate Data Explorer, available at cait.wri.org. Emissions of non-carbon dioxide gases are converted to a carbon dioxide equivalent using a 100-year global warming potential taken from the IPCC Second Assessment Report (1996).

emissions, 36% are from transportation, 16% industrial, 11% residential and commercial, and 36% from electricity.[3, 4]

The damages from GHG emissions stem from the stock of these gases in the atmosphere. Central to understanding the effect of accumulating stocks of CO_2 in the atmosphere on climate change is a scientific parameter known as *equilibrium climate sensitivity*. Equilibrium climate sensitivity (ECS) measures the long-run equilibrium increase in temperature arising from change in the stock of greenhouse gases in the atmosphere. Just as the glass roof of a greenhouse traps solar radiation and raises the temperature inside the greenhouse, carbon dioxide and other greenhouse gases trap solar radiation in our atmosphere and raise the planet's temperature. Hence the reference to "greenhouse gases" and the greenhouse effect of climate change. How fast the temperature rises in response to an increase in the stock of greenhouse gases in the long-run depends on the climate sensitivity parameter.[5]

Over one hundred years ago, Sweden's Svante Arrhenius, a childhood math prodigy and Nobel Prize-winning chemist, made the first estimates of climate sensitivity in his 1906 book, *Worlds in the Making*. Arrhenius estimated the value of the climate sensitivity parameter to be four degrees Celsius—that is, a doubling of greenhouse gases leads to an increase in temperature by four degrees Celsius (just over seven degrees Fahrenheit). He made this calculation notwithstanding the very early state of climate science and lack of current, let alone historical, data on temperature and greenhouse gas concentrations. Arrhenius's estimate of climate sensitivity is remarkably durable. Despite the complexity of modeling climate sensitivity, modern estimates are in the ballpark of Arrhenius's 100-year-old estimate.

[3] These are shares of total GHG emissions as reported in U.S. Environmental Protection Agency (2018), Tables 2-3, 2-4, and 2-5. Shares do not account for any forest or land use sinks.
[4] Electricity is used by the other sectors. If attributed to those sectors, the residential and commercial sectors would tie with transportation as the most carbon intensive sectors (36% each).
[5] ECS measures the long-run equilibrium response. Transient Climate Response (TCR) measures the temperature response over a shorter period. Figure 1 below shows a relationship between carbon concentrations and temperature increase that reflects the TCR relationship.

Pre-industrial era concentrations of carbon dioxide in the atmosphere are typically pegged at 280 parts per million (ppm) though air samples taken from Antarctic ice cores make clear that concentrations have ranged between 180 and 290 ppm over the past 400 thousand years (Petit J.R. et al. (1999)). Current measurements of carbon dioxide have been taken on a continuous basis in Hawaii starting in 1958 when Charles Keeling installed monitoring equipment on the upper slopes of the Mauna Loa volcano 11,000 feet above sea level. The Keeling Curve shows a dramatically rising concentration of carbon dioxide in the atmosphere with current monthly average concentrations topping 405 ppm. Figure 1 shows the relationship between atmospheric carbon dioxide concentrations and global mean temperatures since 1850.[6]

The National Oceanic and Atmospheric Administration (NOAA) publishes a Climate Extremes Index as a way to summarize extreme temperature (high and low), precipitation, drought, and tropical storm intensity with data going back to 1910. Six of the top ten extreme climate years have occurred since 2005 and each of the years since 2015 have been among the top six extreme years. This index highlights the fact that climate change is as much (if not more) about climate variability than it is about warming.

Below, I'll discuss the economic costs of climate policy. Any discussion of policy costs should recognize that failing to act has costs as well. While a detailed analysis is beyond the scope of this paper, a few comments are in order. Until recently, most measures of the damages from GHG emissions were derived from reduced form damage functions embedded in integrated assessment models such as

[6] Carbon dioxide data are taken from Antarctic ice core samples (pre-1958) and the Keeling data as reported at http://scrippsco2.ucsd.edu/data/atmospheric_co2/icecore_merged_products, accessed Feb. 14, 2019. Global mean temperatures from Berkeley Earth available at http://berkeleyearth.lbl.gov/auto/Global/Land_and_Ocean_summary.txt, accessed Feb. 14, 2019. The format of the graph is due to Robert Rohde of Berkeley Earth. A linear regression of the change in temperature from 1850 on the log of the ratio of carbon dioxide concentrations since 1850 yields an estimated 2.5 degree Celsius increase in temperature from a doubling of carbon dioxide concentrations. This regression fit is more akin to the Transient Climate Response (TCR) than the Equilibrium Climate Sensitivity (ECS).

the Nordhaus DICE model. Nordhaus (2013) describes the various cost factors and models damages (as a percent of global output) as an (approximately) quadratic function of temperature increase. In a recent meta-analysis, Nordhaus and Moffat (2017) find no evidence for sharp convexities or discontinuities in the damage function and find damages on the order of 2 percent of global income for a 3 degree C increase in temperature and 8 percent at 6 degrees C. They caution, however, that damage estimates are not comprehensive and, in some areas, little more than guess work. As a result, these damage estimates should be viewed as lower bounds.

Hsiang et al. (2017) construct detailed estimates of the damages from climate change in the United States at the county level and find that the combined market and non-market damages for a one degree C increase in temperature is on the order of 1.2 percent of GDP. Damages are unequally distributed with higher damages in southern areas. By the end of this century, they estimate that the poorest third of U.S. counties have a 90 percent chance of experiencing damages between 2 and 20 percent of county income in a business as usual scenario with no action to reduce emissions.

The cost of climate change includes both damages and the costs of adaptation. As temperatures increase, we can expect to see greater penetration and use of air conditioners – a form of adaptation. Infrastructure investments to cope with more frequent and severe storms of a Sandy type are also forms of adaptation. Adaptations, of course, come with their own cost. The International Energy Agency (2018b) estimates that household ownership of air conditioners will rise from 1.1 billion units in 2016 to over 4 billion units by 2050. The electricity needed to power those new air conditioners exceeds the current electricity consumption in Germany and the United States.

III. Theory

A. Putting a Price on Pollution

Arthur C. Pigou is credited with the idea of using taxes to correct the market failure arising from the presence of externalities in his 1920 book, *The Economics of Welfare.* The problem with pollution is that there is a divergence between the private and social cost of a good due to pollution, with the divergence equal to the marginal damages from the pollution. If this is the problem, argued Pigou, then taxing the pollution at its social marginal damages would equate private and social marginal costs and ensure an efficient market outcome.

For many pollutants, taxing the pollution is difficult if not impossible whereas taxing the good associated with the pollution more practical. Such is not the case, however, for energy-related carbon dioxide emissions. The amount of CO_2 associated with burning a ton of coal, gallon of gasoline, or a therm of natural gas is, for all intents and purposes, constant[7]. Changes in industrial processes may affect the amount of fossil fuel burned but not the emissions per unit of fuel input.[8]

A Pigouvian tax is especially attractive in a situation where it is (relatively) easy to measure the marginal damages from the pollutant but where it is difficult to identify the individuals suffering the damages from pollution. In such an instance, bargaining between the polluter and those affected by pollution a la Coase (1960) cannot substitute for government intervention. Coase understood this:

> In the standard case of a smoke nuisance, which may affect a vast number of people engaged in a wide variety of activities, the administrative costs might well be so high as to make any attempt to deal with the problem within the confines of a single firm impossible. An alternative solution is direct Government regulation. (p. 17)

Put differently, Coasian bargaining requires reasonably low transaction costs (along with clear property rights) for private bargaining to substitute for government intervention. Climate change has especially high transaction costs given the number of people affected (both across countries and across time).

A Pigouvian tax is a market-based instrument to control pollution, in the sense that it allows the market to operate once prices have been adjusted through the use of a Pigouvian tax. A cap-and-trade

[7] Different grades of coal release different amounts of CO_2 per ton burned. But the differences are well understood and limited in number, making it straightforward to apply a carbon tax to coal either at the mine mouth or at the site where burned – or anywhere in between.

[8] The one major exception is carbon capture and storage (CCS), where carbon dioxide is captured when the fuel is burned and permanently stored to prevent its release into the atmosphere. I discuss CCS and its treatment under a carbon tax in section VI.

system is an alternative way to set a price on pollution. Whereas a carbon tax puts a price on CO_2 pollution and lets the market determine the amount of pollution, a cap-and-trade system puts a cap on pollution and lets a market operate in the buying and selling of rights to pollute (subject to the cap) and so determine a market clearing price. The earliest significant cap-and-trade system was the Acid Rain Program, established as part of the Clean Air Act Amendments of 1990.[9] The European Union's Emission Trading System is the largest greenhouse gas cap and trade system established to date.[10] The cap-and-trade concept is credited to the Canadian economist, John Dales (1968).

An extensive literature compares and contrasts a carbon tax and a cap-and-trade policy. While the economic literature suggests that a carbon tax is more efficient ex ante than cap-and-trade in a world with uncertain marginal abatement costs, the relative efficiency of the two instruments depends on underlying modeling assumptions.[11] The efficiency differences between traditional regulation and a market based instrument like a carbon tax or cap-and-trade system are likely to be much greater than the differences between the latter two policies.[12]

Setting aside economic efficiency, three factors favor carbon taxes over cap-and-trade systems.[13] First, a cap-and-trade system fixes emissions but allows prices to vary as market conditions change. This can lead to price volatility and uncertainty for firms who are planning long-lived capital-intensive projects. The Acid Rain Program illustrates the potential for price volatility. Allowance prices

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[9] Schmalensee and Stavins (2013) provide a history and assessment of the Acid Rain Program.
[10] World Bank Group (2018).
[11] The literature comparing efficiency of the two instruments draws heavily on the seminal paper of Weitzman (1974). Weitzman's paper considered a flow pollutant. Papers that extend the Weitzman framework to consider a stock pollutant like greenhouse gases include Hoel and Karp (2002), Newell and Pizer (2003), Karp and Zhang (2005), and Karp and Traeger (2018), among others. Excepting the last paper, the papers tend to favor a price instrument (tax) in the presence of a stock pollutant. Note, too, that the Weitzman framework assumes a once-and-for all decision on a cap or tax schedule. If updating is possible, the differences between the two instruments shrink, if not disappear.
[12] Carlson et al. (2000) suggest that the cost of regulating sulfur dioxide emissions with a cap and trade could be reduced as much as one-half compared to traditional command-and-control regulation. See also Ellerman et al. (2000).
[13] I elaborate on these issues in Metcalf (2019).

have fluctuated anywhere from zero to $1,200 in the five years between 2005 and 2010. Price fluctuations are not limited to the EPA's Acid Rain Program. Allowance prices in the EU's Emission Trading System fell by one-third in one week in April 2006 and a further twenty percent over the next month upon release of information that initial allowance allocations had been too generous.[14]

The second difference between the two policy instruments is in administrative complexity. The United States has a well-developed tax collection system, including systems in place to collect taxes on most fossil fuels. A cap and trade system, in contrast, requires an entirely new administrative structure to create allowances, track them, hold auctions or otherwise distribute them, and develop rules to avoid fraud and abuse. Fraud is a particularly significant problem in a system that is creating brand new assets (emission allowances) worth billions of dollars. This is not just a theoretical concern. In January 2011, the EU had to suspend trading in allowances when $9 million of allowances were stolen from an account in the Czech Republic. EU commissioners noted hackers had also broken into accounts in Austria, Poland, Greece, and Estonia and as much as $40 million of allowances were stolen.[15] While tax evasion is certainly a potential problem, the United States has a strong culture of tax compliance. The risk of cybertheft from electronic registries in a cap and trade system is likely to present a greater problem than the risk of tax evasion in a carbon tax.

The final difference between a carbon tax and a cap and trade system is the potential for adverse policy interactions that can work against our goal of reducing emissions. This is a big problem for cap and trade systems. Let’s say a cap is set with a goal of realizing allowance prices of $40 a ton. That price target would contribute to driving innovation and the development of new carbon free technologies that we’ll need to get to a zero-carbon economy by the end of the century. Investors won’t place risky bets on new energy technologies that reduce emissions unless they can be confident

[14] The price decline is discussed in Metcalf (2009).
[15] The cyber-theft story is reported by Chaffin (2011) and Lehane (2011), among others.

that there's a good chance of earning a high return on that investment. The higher the carbon price, the more confident they can be that their investment will earn a return that will pay for the risk they'll be taking. That's because a high carbon price drives up the cost of natural gas, petroleum, and coal, and can make a new zero-carbon investment competitive in the market even at a cost that is high enough to repay the investor for the risks they took in underwriting a new and unproven technology.

Let's assume the demand for allowances is such that the cap would indeed lead to a $40 per ton allowance price. So far, so good. But then, suppose policy makers decide to tighten the renewable portfolio standard and require a higher percentage of renewable electricity. This is going to reduce the demand for allowances and drive allowance prices down in the cap and trade program.

This is precisely what has happened in the major cap and trade programs. They have all struggled to set a price at a level that drives significant reductions in carbon pollution. Since trading began in 2013 for the current phase of the ETS (2013 – 2020), prices have generally ranged between $3.60 and $8 per ton and only broke through the $10 barrier in March 2018. Prices in the earlier trading period (2008 – 2012) were not much higher. When allowances for this commitment period were first issued, prices rose to nearly $36 a ton but quickly fell by about half and subsequently drifted down.[16]

To address low prices in the EU's Emission Trading System, The EU initiated a program to reduce a surplus of allowances in the system stemming, in part, from the 2008 recession. The EU will reduce the surplus by one-quarter each year between now and 2024 by adding the allowances to a Market Stability Reserve.[17] This has help raise ETS allowance prices to its current level (as of late February 2019) of $21 a metric ton.

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[16] Allowance prices for the 2013 period forward are taken from the European Energy Exchange website available at https://www.eex.com/en/market-data/environmental-markets/spot-market/european-emission-allowances accessed on Jan. 10, 2019. Prices from the 2008 – 2012 period are from Koch et al. (2014). Euro prices are converted to dollars at the rate of $1.15 per euro, the exchange rate as of Jan. 10, 2019.

[17] The announcement of allowances in circulation was published at https://ec.europa.eu/clima/news/ets-market-stability-reserve-will-start-reducing-auction-volume-almost-265-million-allowances_en, accessed on Jan. 14, 2019. See also Lewis (2018). Rules for adding allowances to or withdrawing from the MSR were established in 2015 to

Low prices also bedevil the Regional Greenhouse Gas Initiative (RGGI), a cap and trade system for electricity in the Northeast. The nine states in RGGI committed to capping carbon emissions from the electric power sector beginning in 2009. Proceeds from the emissions allowance auctions are designated to fund energy efficiency and renewable investments in the participating states. Power plants covered under the RGGI program account for roughly one-quarter of greenhouse gas emissions in the region. Allowance prices have ranged between $1.86 and $7.50 a ton. The December 2018 auction had a clearing price of $5.35 a ton. While the program has generated over $3 billion since its inception for state governments participating in RGGI, it is unlikely that the carbon price has contributed to a significant reduction in electricity sector emissions that would not have occurred in the absence of the program.[18] Moving to the West coast, California's cap and trade program has tried to address the pricing problem that has plagued the EU and RGGI. They've had limited success. The settlement price for allowances in the November 2018 auction was $15.31 a ton.[19]

These programs are not unique in experiencing low allowance prices. The World Bank's 2018 annual review of carbon pricing tracks carbon pricing in roughly forty countries and twenty cities, states, and regions. The highest carbon price among the cap and trade systems surveyed in the review is about $16 a ton. In contrast, five countries have carbon tax rates of at least $50 a ton with Sweden leading the group at $140.

One reason allowance prices persist at low levels is human nature. Politicians like to *do things*. When they see a problem, they want to enact a policy to fix it. So, you see complementary policies put

go into operation in 2019. As of May, 2018, the EU has estimated that over 1.6 billion allowances were in circulation. Allowances in excess of 833 million are deemed surplus and subject to being added to the MSR.

[18] Cullen and Mansur (2017) show that a carbon price of $20 a ton would be needed to effect a five percent reduction in electricity emissions. With an average clearing price of $5 a ton, RGGI might have reduced emissions by one percent or so. That works out to at most a roughly one million ton reduction in carbon dioxide per year – about 0.3 percent of total CO_2 emissions from those states in the year.

[19] RGGI's prices are posted at http://rggi.org. California's auction results are posted at https://www.arb.ca.gov/cc/capandtrade/auction/auction.htm#proceeds.

in place to reduce emissions. These policies include subsidies for renewable electricity generation, energy efficiency programs, and motor vehicle fuel economy standards, to name a few. These complementary policies reduce emissions and so reduce demand for allowances in a cap and trade program. That in turn depresses allowance prices. While helpful for reducing the impact on consumers, this policy interaction creates two problems. First, persistently low allowance prices undercut the private sector's incentive to innovate and bring to market low and zero carbon technologies. Second, the policy interaction undercuts the complementary policy. Consider a renewable portfolio standard implemented in Spain that requires a percentage of Spanish electricity be generated from renewable sources. Since the electricity sector is part of the EU-wide cap and trade system, any reduction in demand for coal or natural gas fired electricity in Spain simply loosens the overall EU cap on emissions and allows firms elsewhere in Europe to burn fossil fuels. Complementary policies are not a problem for a carbon tax. Layering an additional policy on top of a tax does not affect the tax's price signal and incentive to reduce emissions.[20]

The most powerful argument in favor of cap and trade programs over carbon taxes are that: 1) prices are not being set directly by politicians and so political distance is created for risk-averse policy makers; and 2) allowances created in a cap and trade program are valuable assets that policy makers can distribute in ways to reduce political opposition. The Acid Rain Program created roughly ten million allowances in the year 2000, for example. With an average spot price of just under $145 a ton, the allowances disbursed that year were worth $1.45 billion. The Acid Rain Program distributed allowances for free to owners of coal-fired power plants based on their historic coal use. This certainly eased opposition to the program. Using allowances to overcome opposition was behind the complex allocation process in the American Clean Energy and Security Bill (HR 2454), the cap and trade bill passed by the House of Representatives in 2009 that ultimately failed in the Senate. A free allowance

[20] See Burtraw and Keyes (2018) for further discussion.

allocation can help grease the political wheels and contribute to passage of cap and trade legislation. But this is very expensive grease! The Congressional Budget Office estimated that the value of the free allowances in that bill would be nearly $700 billion over a ten-year period.[21]

Giving allowances to polluting firms for free raises important distributional questions. Giving firms $700 billion in free allowances has the same effect on their bottom line as giving them cash. The result is a windfall for shareholders: profits and share prices go up. This is what happened in Europe when the European Union set up its carbon dioxide cap and trade program and gave allowances to the firms that were subject to the cap.[22] Whether this is fair is a matter of debate. But the very complexity of the cap and trade approach means that the public didn't really understand the massive transfer taking place in the EU's ETS or that would have taken place had the U.S. cap and trade legislation gone into effect.

B. Regulation

While the focus above has been on market-based instruments, the reality is that most of the polices to address climate change rely on various forms of regulation, subsidies, and voluntary actions or information. The two most important regulations that have been put forward to address GHGs at the federal level are corporate average fuel economy (CAFE) standards, and regulation of CO_2 emissions in the power sector under the Clean Air Act. Recall that transportation and electricity generation each accounted for 36 percent of energy-related carbon dioxide emissions in 2016. These two regulatory targets, thus account for nearly three-quarters of these emissions.

Following a Supreme Court ruling in 2007 that ruled that greenhouse gases were air pollutants that could be regulated under the Clean Air Act, the EPA in 2009 issued an endangerment finding

[21] Congressional Budget Office Cost Estimate of H.R. 2454, June 5, 2009. Available at https://www.cbo.gov/publication/41189.
[22] Smale et al. (2006) examine five energy-intensive sectors in the UK and conclude that profits in most of the sectors rise following the imposition of a cap and trade system with free allowance allocation.

determining that GHGs should be subject to regulation and began the process of promulgating regulations. Numerous papers have been written on the relative inefficiency of fuel economy regulation relative to a Pigouvian tax – see, for example, the recent review by Anderson and Sallee (2016). Whereas taxes on emissions – in transportation this can be translated into a tax on gasoline use – creates incentives for consumers to purchase more fuel-efficient vehicles, drive fewer miles in aggregate, and scrap fuel inefficient vehicles sooner. A fuel economy standard mandating that an auto-maker's vehicle fleet must meet minimum fuel economy standards in toto also incentivizes the purchase of more fuel-efficient vehicles. But the higher fuel economy drives down the cost of driving per mile and so can lead to more driving – the rebound effect. Moreover, fuel economy standards only apply to new vehicles. This increases the value of fuel-inefficient vehicles already on the road and delays their eventual scrappage, an effect first pointed out by Gruenspecht (1982). All in all, these factors lead to fuel economy standards being less cost effective than an emissions tax for achieving given emission reductions. Karplus et al. (2013), for example, find that fuel economy standards are six to fourteen times more expensive than a fuel tax to achieve the same emission reductions.[23] Jacobsen (2013) finds CAFE is a little over three times the cost of a gasoline tax per ton of carbon dioxide avoided in a model where technology can respond to the mandate or higher fuel costs.

The Obama Administration imposed tighter fuel economy standards for cars and light trucks for model years 2022-2025 that would have raised the fleetwide average to 54.5 miles per gallon for 2025. This essentially would double fuel economy from the Model Year 2011 fleet standards of 27.3 miles per gallon.[24]

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[23] Federal policy also includes various tax provisions that create an explicit or implicit tax on fuel economy. Sallee (2011) reviews these and notes that the inefficiency is exacerbated by gaming resulting from the way the taxes are designed.

[24] Federal Register Vol. 74, No. 59, pp. 14196 – 14556. MY2022-25 standards described at https://web.archive.org/web/20130305181919/http://www.nhtsa.gov/About+NHTSA/Press+Releases/2011/President+Obama+Announces+Historic+54.5+mpg+Fuel+Efficiency+Standard, accessed Jan. 14, 2019.

In August, 2015, the Obama Administration released the Clean Power Plan, a set of EPA regulations to cut GHG emissions from existing electric power plants.[25] The plan used "building blocks" of potential emission reduction channels including efficiency improvements in boilers, generation shifting (from emissions intensive fuel sources to less intensive sources), and increased generation from new low or zero-emitting sources. Based on EPA's analysis of the potential for emission reductions in each state, targets were set that could be in the form of emission rate standards, mass-based standards, or a "state measures" standard. States could also join together to create a regional cap-and-trade program which, in the limit, could mimic a national cap-and-trade program for the electric generating sector. Bushnell et al. (2017) show that individual states might find it advantageous not to join a coalition cap-and-trade system, thereby undermining the potential for efficiency gains. In a simulation of the Western power grid, the authors find that a state-by-state cap-and-trade system is 19 percent more costly than a national cap in a mass-based system. All this is moot, however, as then-EPA Administrator Scott Pruitt issued a proposed rule to repeal the Clean Power Plan in October 2017.[26] Since the endangerment finding is still in place, EPA is required to propose a new rule. We can expect litigation no matter what approach the Trump Administration takes to water down if not eliminate GHG regulations for the power sector.

The CAFE fuel economy regulations and Clean Power Plan illustrate a political vulnerability to using regulation to advance mitigation goals. In August 2018, the Trump Administration announced a reworking of the MY2022-25 standards as the Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule that would freeze fuel economy standards at the MY 2020 levels through MY 2026.[27] States are currently fighting this rule rollback in the courts. And, as noted above, the Trump Administration is working to eliminate the Clean Power Plan. Executive action using regulatory authority is subject to the political

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[25] The final plan was published in the Federal Register on Oct. 23, 2015 (v. 80, No. 205), pp 64661-65120.
[26] Eilperin (2017).
[27] See https://www.nhtsa.gov/laws-regulations/corporate-average-fuel-economy, accessed Jan. 14, 2019.

risk of changes in administration that can lead to a new reading of laws and consequent changes in enforcement and stringency. Meanwhile, opponents of the rule changes (whether made by the Obama or Trump Administration) have challenged the changes in the courts thereby adding to the policy risk and uncertainty.

C. Subsidies

Subsidizing activities that compete with the polluting activity can reduce pollution and is particularly attractive to politicians. After all, subsidies generally lower costs for their constituents. The problem, however, is that someone has to pay for the subsidy. These costs, in general, are spread across many people and so while the aggregate cost of the subsidy might be large, the cost to any individual may be too small to notice.

Renewable Portfolio Standards (RPS, for short) are common policies at the state level. RPS programs are a blend of regulation and subsidy and are currently in place in twenty-nine states.[28] An RPS policy mandates that a certain fraction of the electricity sold in the state must come from a designated renewable source such as wind or solar. Massachusetts, for example, has a requirement that every private company selling electricity in the state in 2020 must prove it has satisfied its fifteen percent RPS obligation. Companies demonstrate compliance by submitting *renewable energy credits* (or RECs) to the state each year. RECs are like vouchers that the state gives to renewable electricity producers for every megawatt-hour (1000 kilowatt-hours) of electricity the renewable facility generates. The owners can then sell those vouchers to electricity distribution companies that buy as many RECs as they need to comply with the state law. The payment from the company that sells electricity to retail customers is a payment over and above the payment for the electricity that the renewable generator sells into the system. An owner of a commercial solar farm selling electricity into the grid might get paid between two to ten cents per kilowatt-hour depending on the time of day the power is sold. The owner

[28] http://programs.dsireusa.org/system/program/detail/479

could also sell a REC to some utility that needs it to comply with the RPS rule. That might bring another twenty-five to twenty-eight cents per kilowatt-hour (based on solar REC prices in 2014 in Massachusetts). The cost of the REC gets folded in to the cost of generation and passed on to ratepayers.

While the REC costs get passed on to ratepayers, the cost increase is blunted to some extent by the fact that wind and solar have very low (essentially zero) operating costs. As a result, electricity prices don't go up as much as when a tax is imposed. Keeping prices down discourages firms and individuals from investing in energy efficiency to reduce consumption. And while a tax increase may be unpopular, it does raise revenue that could be returned to ratepayers in a way that preserves the energy-saving price signal while also offsetting the income loss from higher electricity rates. Blunting the price signal raises the cost of RPS emission reductions relative to a carbon tax. A recent study found that the cost of cutting carbon emissions in the electricity sector by ten percent was over six times higher with an RPS program than with a carbon tax applied to fuels used to generate electricity.[29]

Rather than have the ratepayer pay for the subsidy as in RPS programs, we can have taxpayers finance it. Since the first energy crisis back in the 1970s, Congress has provided tax breaks to encourage various energy technologies including breaks for developing and using renewable technologies.[30] Historically, the biggest tax breaks have been tax credits for projects that generate electricity from solar, wind, geothermal, or other renewable sources. Currently, solar electricity and solar hot water projects

[29] Reguant (2018) carries out the study comparing RPS and carbon taxes in the electricity sector. Fischer (2010) has shown that RPS programs can actually reduce electricity prices since the price of wind or solar at the margin is zero in contrast to natural gas which, while cleaner than coal, still has a cost at the margin.

[30] Since the inception of the tax code there have been large tax breaks for domestic oil and gas drilling. Metcalf (2018) shows that these incentives have had modest impacts on domestic oil and gas production but are costly to the U.S. Treasury.

are eligible for a thirty percent *investment tax credit*.[31] This credit is available for residential rooftop solar as well as utility-scale solar projects (e.g. a solar farm).

The tax subsidy for wind operates differently. A wind project that began construction in 2016 can earn a *production tax credit* of 2.3 cents per kilowatt-hour of electricity generated during its first ten years of operation. That is over and above the revenue it gets from selling electricity into the grid.

Subsidies to clean energy are problematic. The first and most obvious problem is that subsidies *lower* the end-user price of energy rather than *raise* it. In Texas, a wind-rich area with lots of installed wind capacity, generators have willingly accepted a *negative* price for their electricity when demand was very low, say in the middle of the night. That's because the wind generators have next to zero operating costs and can collect 2.3 cents in production tax credits for every kilowatt-hour they sell. Even if they have to pay a penny to provide electricity, they are still earning 1.3 cents on each kilowatt-hour sold after cashing in on the production tax credit.[32]

Lowering consumer prices encourages more energy use. It also means consumers buy fewer energy efficient appliances and factory owners invest less in energy efficient equipment. Subsidies are also expensive. Production and investment tax credits reduce federal tax collections by about $3 billion a year.

Subsidies have other problems. They pick winners and losers among competing technologies – thus violating technological neutrality. If our goal is to cut carbon emissions, we should reward technologies that cut emissions regardless of how those technologies work.

Another problem with subsidies is that they are wasteful with a significant share of the subsidy going to inframarginal purchasers of the capital asset. Consider the $7,500 subsidy for the purchase of a

[31] The taxpayer must have adequate tax appetite to use the credit. If tax credits exceed taxes owed, the excess credit can be carried forward and used it in future years. Alternative minimum tax considerations historically also affected the ability to use tax credits, as discussed in Carlson and Metcalf (2008).

[32] The problem is not unique to Texas. Wald (2012) reports that the Chicago area experienced negative pricing three percent of the time in 2010.

plug-in hybrid vehicle. If the subsidy induces only one in five people to buy a plug-in hybrid, then the effective cost is five times the subsidy or $37,500 – more than the cost of low-end plug-in hybrids.

The problem is that we can't target the subsidy to the prospective car buyer who will be motivated to buy only because of the subsidy. So, every buyer gets it. We don't really know whether half the sales would have occurred without the subsidy or eighty percent. For newer innovative technologies, one-half may be the right number. But for more common technologies like energy efficient windows and appliances that have been subsidized through the tax code, a rule of thumb that four out of five of the sales would have taken place anyway is more reasonable.[33]

Besides being wasteful, energy subsidies disproportionately accrue to high income households. A 2016 analysis of tax returns show that ten percent of energy tax credits go to the bottom sixty percent of the income distribution while nearly two-thirds go to households in the top twenty percent.[34]

Subsidies can also interact with regulations in unexpected ways. For example, policies that appear complementary can actually undercut each other. Consider the federal tax credit for plug-in hybrids and electric cars. This credit makes it more attractive to buy electric cars and plug-in hybrids. Meanwhile, auto manufacturers are subject to fleet-wide fuel economy standards under the federal CAFE program. For every Chevrolet Bolt in Massachusetts in part because of the federal credit, General Motors can now sell a gas-guzzling car to someone elsewhere. The purchase of the Bolt raises the

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[33] This may be too conservative. Consider energy efficient windows. Let's say a homeowner spends $2,000 to replace some older windows with energy efficient windows. A tax credit (that expired at the end of 2016) worth $200 was available for those windows. Assuming a (generous) price elasticity of -1.0, meaning demand rises by one percent for each one percent reduction in price, this credit would induce just over ten percent in new sales. In other words, nine sales out of ten would have occurred in the absence of the subsidy. So, for the one sale of $2,000 in energy efficient windows that was generated by the tax credit, the government paid out $2,000 in tax credits for windows. This is consistent with the findings in Houde and Aldy (2017) that seventy percent of consumers claiming rebates for an energy efficient appliance would have bought them anyway and another fifteen to twenty percent simply delayed their purchase by a couple of weeks to become eligible for the rebate. Other research showing a high fraction of purchases that benefit from but are not influenced by a subsidy include studies by Chandra, Gulati, and Kandlikar (2010) and Boomhower and Davis (2014).
[34] This study was done by Borenstein and Davis (2016). Some tax credits are more regressive than others. The researchers document that ninety percent of the credits for electric vehicles go to households in the top twenty percent of the income distribution.

overall fuel economy of the fleet, and General Motors is subject to a nation-wide mandate on the overall fuel economy of the vehicles it sells.[35]

D. Information and Voluntary Programs

Energy experts and policy makers have increasingly focused on the potential for carefully packaged information to reduce energy consumption. While information is valuable, it is not a viable climate policy. Allcott and Rogers (2014), for example, show that these programs yield about a two percent savings in energy – helpful, but not an approach that is going to get us to a zero-carbon economy.

Offsets are another popular voluntary program. A carbon offset is a payment someone can make to a company to reduce emissions to offset the buyer's own emissions. The problem with offset programs is that it is difficult, if not impossible, to verify that real emission reductions will occur from your offset payment. Moreover, trading in offsets is miniscule related to the emissions reduction need.[36]

IV. Carbon Taxes Around the World

Carbon taxes have been used by countries and sub-national governments for more than twenty-five years. As of early 2019, twenty-seven national or sub-national carbon taxes were currently in effect.[37] There have been two waves of carbon tax enactments: a Scandinavian wave starting in the early 1990s saw carbon taxes legislated in Denmark, Finland, Norway, and Sweden among other countries. By 2000, seven countries had a carbon tax. A second wave in the mid-2000's saw carbon taxes put in place in Switzerland, Iceland, Ireland, Japan, Mexico, and Portugal. In addition, the

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[35] It's actually better than that for General Motors. For greenhouse gas emissions fleet limits, EPA treats each 2017 plug-in hybrid sold as if it were 1.7 cars. Electric cars are treated as two cars. And they have a low emission factor (zero for electric) even if the electricity that charges the batteries comes from coal fired power plants. For fuel economy, the National Highway Transportation Safety Administration, the agency in charge of overseeing fuel economy standards, doesn't apply a multiplier but does ramp up the fuel economy by dividing the car's estimated fuel economy by 0.15. So, an electric car that is rated at forty-five miles per gallon gets treated as if it gets 45/0.15 = 300 miles per gallon. For more information, see https://www.c2es.org/federal/executive/vehicle-standards, accessed Jan. 14, 2019.

[36] I discuss this in greater detail in Metcalf (2019).

[37] Existing and planned carbon tax regimes is summarized in World Bank Group (2018).

Canadian provinces of British Columbia and Alberta have enacted carbon taxes. In 2019, Argentina implemented a carbon tax and Singapore and South Africa are scheduled to implement carbon taxes this year. A South African parliamentary committee moved carbon tax legislation forward so that the full Parliament may consider the tax sometime in 2019 (Szabo (2019)). Globally, tax rates range widely from Poland's carbon tax rate of less than one dollar per ton of carbon dioxide to as much as $139 per ton for Sweden. Twelve countries have carbon tax rates of at least $25 per ton with six with rates of at least $50 per ton.[38]

Given the range in carbon tax rates around the world, how should the United States set the tax rate should it implement a carbon tax? Pigouvian theory suggests the tax on carbon pollution should be set equal to the marginal damages from one more ton of carbon dioxide emissions.

In a world with pre-existing market distortions, economists have argued that the optimal tax on pollution (of any type) will typically be less than the marginal damages.[39] Specifically, the optimal tax equals the marginal damages of pollution divided by the marginal cost of public funds. The larger are tax distortions, the larger the marginal cost of public funds and the smaller the optimal tax relative to marginal damages.[40]

Whether one uses a first or second best Pigouvian approach, policy makers need an estimate of the marginal damages from carbon dioxide emissions. They could base their estimate on analyses of the social cost of carbon (SCC) done by the U.S. EPA and other federal agencies during the Obama Administration. This is a measure of damages designed for use in regulatory benefit costs analyses as

[38] Rates are as of April 1, 2018 as reported in World Bank Group (2018).

[39] The first papers to make this point were Bovenberg and de Mooij (1994) and Parry (1995).

[40] See Bovenberg and Goulder (2002) for a review of the literature on second-best environmental taxation and, in particular, section 2. As a central case, Bovenberg and Goulder (1996) estimate the marginal cost of public funds to equal 1.25 suggesting the optimal tax on pollution should be 20 percent lower than social marginal damages. The first-best rule that sets the tax on pollution equal to social marginal damages can be recovered if households have identical tastes, leisure is weakly separable from pollution and private goods, and a non-linear income tax can be imposed such that the benefits of the pollution tax are exactly offset by the income tax to achieve distributional neutrality. See, for example, Kaplow (1996) and Pirttila and Tuomala (1997). As Bovenberg and Goulder (2002) point out, these conditions – especially the last – are unlikely to be met.

opposed to the Pigouvian prescription to measure the social marginal damages of emissions at the optimal level of emissions. The errors in measuring social marginal damages at current emission levels rather than optimal levels is likely to be swamped by errors in estimation from our imperfect state of knowledge about the full range of damages and risks of catastrophic events – events with high impact but low probability.[41] With that caveat in mind, a tax rate based on the SCC would be roughly $50 a metric ton of carbon dioxide in 2020.[42]

A second approach would be to set a tax rate to hit a revenue target over a ten-year budget window. The U.S. Department of Treasury study projects that a carbon tax starting at $49 a metric ton in 2019 and rising at 2 percent (real) annually, would raise $2.2 trillion in net revenue over the ten year budget window (Horowitz et al. (2017)). This is net of reductions in other tax collections due to the carbon tax.

Alternatively, a sequence of tax rates could be set over time to achieve a given reduction in emissions by some date. International climate negotiators have focused on a global goal of reducing emissions by eighty percent relative to 2005 by 2050. The United States set this as an aspirational goal in the promises it made in 2015 as part of the international climate negotiations that led to the Paris Agreement. Most economic analyses suggest that given the current state of technological progress, an eighty percent reduction by 2050 would be extremely costly. Whether policy makers settle on an eighty

[41] Much has been written on the implications of high impact, low probability events – sometimes referred to as fat tail events. See Wagner and Weitzman (2015) for a lively summary of the literature and a clear statement of the view that climate policy should be viewed as an insurance policy rather than as a Pigouvian price adjustment.

[42] The $50 figure is based on the U.S. Interagency Working Group on the Social Cost of Carbon (2016) estimate for 2020 equal to $42 in 2007 dollars. I've converted the estimate to 2020 dollars using the CPI deflator. This is not precisely the right estimate given the methodology used by the Interagency Working Group but it is close enough given the uncertainties discussed in the text. This also ignores second-best considerations that lead to estimates of the optimal tax on emissions to fall short of social marginal damages as discussed in footnote 22 above. Pindyck (2017) is a prominent critic of using the Interagency Working Group's methodology to set the tax rate on carbon dioxide. He suggests convening an expert panel to recommend values rather than rely solely on computer modeling of damages.

percent reduction by 2050 or some other target, a carbon tax will likely be designed with some emissions reduction target in mind.

Let's assume that's the case. How do you ensure you hit the target given our use of a carbon tax? One way to do that is to enact a carbon tax with a "policy thermostat" that adjusts the tax rate in a known and predictable way between now and some future date to increase the likelihood of hitting emission reduction targets 15 to 30 years out.[43]

Next, I describe three carbon tax systems in some detail. They are unique in various ways. British Columbia has a carbon tax on emissions associated with provincial consumption; its tax is one of the most broad-based carbon taxes in place. Switzerland's carbon tax has a unique feature of a tax rate that is adjusted statutorily if emission reduction goals are not met. Sweden's carbon tax has the highest carbon tax rate in the world and has gradually moved to eliminate all discounted rates for energy-intensive sectors subject to the tax.

A. British Columbia

As part of a broader package of tax reforms, the Canadian province of British Columbia enacted a broad-based carbon tax in 2008 starting at $10 (Canadian) per metric ton of carbon dioxide and increasing by $5 per year to its current $35 in Canadian dollars (as of 2018), equivalent to $27 in U.S. dollars.[44] The tax is scheduled to increase by $5 (Canadian) per year until it reaches $50 per ton in 2021. The tax is a broad-based tax on the carbon emissions of all hydrocarbon fuels burned in the province. Given the existing federal and provincial taxes already in place, the carbon tax raised the overall excise tax on gasoline by roughly one-fifth.

[43] I propose such a rate adjustment mechanism, called an Emissions Assurance Mechanism, in Metcalf (forthcoming).

[44] All currency conversions to US dollars (CD1 = USD 0.78) use exchange rates as of late May 2018. Information about the tax rate taken from https://www2.gov.bc.ca/gov/content/environment/climate-change/planning-and-action/carbon-tax, accessed May 23, 2018.

The tax collects over $1 billion annually – over five percent of provincial tax collections – and all the revenue is returned to businesses and households through a combination of tax rate reductions, grants to businesses and households, and other business tax breaks. Worried that the new carbon tax would disproportionately affect low income households, policy makers included several elements in the tax reform to offset adverse impacts on them. One element was a low-income climate action tax credit of $115.50 per adult plus $34.50 per child, which reduced taxes by $300 for a low-income family of four. In addition, tax rates in the lowest two tax brackets were reduced by five percentage points. Also, in the first year of the carbon tax, there was a one-time "climate action dividend" of $100 for every BC resident. This equal-sized dividend represents a greater share of the disposable income of low-income households than that of higher income households.

Meanwhile, business tax rates were cut. The tax rate for small businesses, for example, was cut from 4.5 percent to 2.5 percent in 2008. As the carbon tax rate rose from $10 to $20, there was more carbon tax revenue to rebate, much of which was channeled to businesses in the form of new business tax credits.

British Columbia's carefully constructed policy package to return tax revenue to its residents and businesses balanced concerns about distributional impacts and economic growth. Targeting tax cuts to low income households ensured the burden of the tax wouldn't fall disproportionately on these households. And the focus on small business emphasized the importance of supporting economic growth.

Canada is moving to a national price on carbon pollution. As of April, 2019, every province will have to have a plan in place to price carbon emissions. Failing that, the national government will impose a tax at 20 Canadian dollar per metric ton (Wingrove (2019)). Because British Columbia has a carbon tax in place, the federal tax will not be operative in the province.

B. Switzerland

Switzerland introduced a carbon tax in 2008 on fuels used for stationary sources (i.e., not transportation). Carbon intensive firms can opt out of the tax in return for committing to specific emission reductions or – for large energy-intensive firms – by participating in the Swiss cap-and-trade system.[45] One third of the revenue collected (up to CHF 450) is allocated to building efficiency and renewable energy programs. A small amount (CHF 25 million) is set aside for a technology fund. The remainder is redistributed to the public through lump-sum payments to individuals and employer payroll rebates. In 2014, for example, businesses received a payroll rebate of 0.573 percent while participants in the Swiss mandatory health insurance system received a rebate of CHF 46 per insured person (Carl and Fedor (2016)).

In addition to rebating revenue in a lump-sum fashion to businesses and individuals, the Swiss carbon tax is distinctive in linking its tax rate to emission reduction goals. An emissions target provision was added in a 2011 revision of the law: if emissions in 2012 exceeded 79 percent of 1990 emissions, the tax rate would increase to sixty CHF as of January 1, 2014. Emissions did overshoot the target and the tax rate was increased. Subsequent tax rate increases in 2016 and 2018 were predicated on emission targets as detailed in Table 1. The current tax rate in 2019 is 96 CHF (USD 99).[46] The Swiss tax provides an example of a hybrid carbon tax where rates adjust in response to deviations from desired targets (hence, a hybrid of a tax and cap-and-trade system). I discuss a possible hybrid carbon tax design feature in section VI below.

C. Sweden

[45] Information about the Swiss carbon tax comes from the Swiss Federal Office of the Environment at https://www.bafu.admin.ch/bafu/en/home/topics/climate/info-specialists/climate-policy/co2-levy.html, accessed Feb. 14, 2019.

[46] *Ordonnance sur la Reduction des Emissions de CO_2,* Le Conseil Federal Suisse, enacted on December 23, 2011 (RS 641.71) accessed Sept. 14, 2018. Tax rates reported in International Energy Agency (2018a), p. 278. Currency exchange rate as of mid-September 2018.

Sweden enacted a carbon tax in 1991 as part of a wave of early carbon tax adoptions. Like many other early enactors, it used the revenue to lower marginal income tax rates. The general tax rate rose from rate of SEK 250 (USD 27) to its current rate of SEK 1180 (USD 127).[47]

Sectors covered under the EU Emissions Trading System are exempt from the tax. Other industrial sectors were initially subject to a lower rate (one-quarter of the standard rate). The rate differential has gradually been narrowed until it was eliminated in 2018.[48] While the general rate today is 4.72 times its initial rate, carbon tax collections in 2017 are 3.4 times collections in 1994 (the first year for which the Swedish tax authority publishes data.[49] The slower growth in collections despite the gradual narrowing of the rate differential between the general tax rate and the lower industrial rate reflects reductions in emissions in the Swedish economy.

Sweden is notable for having one of the highest (if not the highest – depending on exchange rate) carbon tax in the world. Its GDP has grown by nearly 80 percent since it enacted a carbon tax in the early 1990s, while its emissions have fallen by one-quarter.[50] Sweden's growth rate has exceeded that of the U.S. since 2000 despite high taxes on carbon pollution, in part because Sweden uses the revenue to cut other taxes. And the World Economic Forum (2018) finds the two economies to be about equally competitive. Swedish economist Thomas Sterner notes that while fossil fuels used for home heating are part of the tax base, little in the way of carbon tax is collected on home heating fuels due to a shift away from fossil fuels for this purpose, a shift Sterner argues is due largely to the carbon tax.[51]

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[47] Exchange rate of SEK 1 = USD 0.11 as of Feb. 13, 2019.
[48] Information from https://www.government.se/government-policy/taxes-and-tariffs/swedens-carbon-tax/, accessed Feb. 13, 2019.
[49] Carbon tax data downloaded from https://skatteverket.se/omoss/varverksamhet/statistikochhistorik/punktskatter/energiskatterochandramiljorelateradeskatter.4.3152d9ac158968eb8fd24b2.html on Feb. 14, 2019.
[50] Swedish GDP data from the World Bank and emissions data from Statistics Sweden (http://www.statistikdatabasen.scb.se), accessed Jan. 25, 2019.
[51] Personal communication, Feb. 12, 2019.

Brannlund, Lundgren, and Marklund (2014) find that between 1990 and 2004, Swedish manufacturing output rose by 35 percent while emissions fell by 10 percent for a 45 percent improvement in emissions intensity. Regression analysis finds that the carbon tax played a significant role in explaining this improvement in emissions intensity. The electric, chemical, and motor vehicles sectors had the highest improvements in emissions intensity while paper and pulp had the lowest improvements in emissions intensity (albeit a positive improvement).

V. Economic Outcomes of a Carbon Tax

The literature on the economic impacts of a carbon tax are somewhat thin, in part since few broad-based carbon taxes have been in place for a long enough time to assess. Below I present some regression estimates for emissions and GDP for the Canadian province of British Columbia. Its tax has been in place since 2008 and is a broad-based tax on fossil fuels consumed in the province (based on carbon content). I also report evidence from studies of other taxes.

In addition to econometric studies, I report results from recent modeling economic efforts have shown. The Stanford Energy Modeling Forum (EMF) recently completed a major study (EMF32) of economic outcomes from a U.S. carbon tax. McFarland et al. (2018) describe the study and the 11 economic models that took part. Results from economic modeling (typically, computable general equilibrium models) are useful in that they can model technology innovation and general equilibrium responses that econometric studies typically will not. On the other hand, model results are driven by model assumptions which may not always be perfectly transparent.

1. Emissions

Barron et al. (2018) summarize results from Stanford University's EMF 32 study of a U.S. carbon tax. The eleven models participating in the study found that a carbon tax implemented in 2020 at $25 per ton on energy related fossil fuels would immediately reduce emissions by 6 to 18 percent.[52] A $50 per ton tax yields an 11 to 25 percent decrease in emissions in 2020. Over a ten-year period, the models in the EMF study find that a carbon tax starting at $25 per ton and rising at an annual real rate of 1 percent would lower emissions over the decade (relative to the reference scenario) by 11 to 30 percent, depending on the model, with an average decline of 18 percent. For a $50 per ton carbon tax rising at 5 percent per year, the ten-year emissions decline ranges from 22 to 38 percent with an average of 30 percent (Table 1, Barron et al., 2018).

The immediate declines are quite large and likely reflect fuel switching in the electricity sector as natural gas drives coal out. To appreciate the magnitude of the immediate impact (and the impacts over the decade), consider the following calculation. The aggregate consumer price of fossil fuels in 2020, based on the reference scenario of EIA's 2018 Annual Energy Outlook, is $13.87 per million BTUs.[53] Based on the average carbon dioxide content of each fossil fuel, a carbon tax of $25 ($50) translates into $1.86 ($3.73) per million BTUs of fossil fuel consumption. A $25 per ton carbon tax would increase the consumer price of fossil fuel energy by 13 percent if fully passed forward to consumers. This suggests an emissions price elasticity of $-\frac{.12}{.13} \cong -1.0$, using the midpoint of the immediate emission reduction estimates. The ten-year elasticity (based on the average of the study estimates) is approximately -1.5. Using the $50 a ton carbon tax, the immediate emissions price elasticity is -0.67 and a ten-year elasticity is -1.11.[54,55]

[52] Barron et al. (2018) report emission reductions of 16 to 28 percent below 2005 levels (p. 9). Reference level emissions are approximately 10 percent below 2005 emissions according to Figure 2 in McFarland et al. (2018).

[53] Prices are consumer prices for non-metallurgical coal, gasoline, and natural gas (Table 3). Consumption shares on a BTU basis are used to average the prices (Table 1).

[54] The $25 carbon tax is modeled to grow at 1 percent real so equals $28 at the end of the decade. The $50 rate is modeled to grow at 5 percent real and equals $81 at the end of the decade. If I compute the ten-year elasticity for the $50 rate using the average of the initial and final rates, I get a price elasticity estimate of -0.86.

[55] An early study of an actual carbon tax was the study of the Norwegian carbon tax undertaken by Bruvoll and Larsen (2004). They estimate that emissions have fallen by 2.3 percent relative to a counterfactual of a zero-carbon tax between 1990 – 1999 with changes in the energy mix and energy intensity driving the decline. The Norwegian carbon tax varies across fuels with the 1999 rate ranging from $51 a metric ton for gasoline to $10 – 19

Turning to econometric analyses of existing taxes, Lin and Li (2011) run difference-in-difference regressions of the log difference in emissions in various European countries. Regressions are run for each country individually that imposed carbon taxes in the 1990s (Finland, Netherlands, Norway, Denmark, and Sweden) with 13 European countries selected as controls. Regressions are run over the 1981 – 2008 timeframe. In four of the five countries, the growth rate of emissions falls by between 0.5 and 1.7 (based on the estimated coefficient of the interaction variable). Only the estimate for Finland is statistically significant at the 10 percent level with the coefficient suggesting a drop in the growth rate of emissions of 1.7 percent. The coefficient for Norway is positive but trivially small and statistically insignificant at the 10 percent level. The authors argue that the larger effect for Finland reflects the smaller number of exemptions from the tax than in other countries.

Martin, de Preux, and Wagner (2014) consider the impact of the UK Climate Change Levy (CCL) on various manufacturing firm energy and emissions indicators. Adopted in 2001, the CCL is a per unit tax on fuel consumption by industrial and commercial firms. Unlike a carbon tax, the rate per ton of carbon emissions varies across fuels from a low of £16 per ton for industrial coal use to a high of £30 (natural gas) and £31 (electricity). They find that CO_2 emissions fall by 8.4 percent, albeit imprecisely estimated. Given the differential carbon tax rates on electricity (£31 per ton) and coal (£16 per ton), we can't rule out the possibility that the CCL led to fuel substitution *away* from electricity towards coal.[56]

Rivers and Schaufele (2015) consider the impact of British Columbia's carbon tax on the demand for gasoline in the province using data at the province-month level between January 1990 through December 2011. The authors regress log consumption on a carbon tax exclusive price of gasoline and a price on the carbon contained in gasoline. While a one cent per liter increase in the price of gasoline

for heavy fuel oils. Coal for energy purposes was taxed at $24 a ton. Bruvoll and Larsen estimate an average tax across all sources in 1999 of $21 a ton. Roughly two-thirds of Norwegian CO_2 emissions were subject to some level of tax.

[56] The coefficient on the treatment variable in a regression with a measure of solid fuel use (coal and coke) as the dependent variable is positive but not statistically significant.

depresses gasoline consumption in British Columbia by 0.41 percent, a one cent per liter in the carbon tax reduces demand by 1.7 percent – a four-fold increase. The authors attribute the difference to the high salience of the carbon tax.

Looking at province-level emissions, Elgie and McClay (2013), updated in Elgie (2014), show that 2013 per capita fuel use subject to the carbon tax declined by over 15 percent relative to 2007 levels while comparable fuel use in the rest of Canada rose modestly. They did not control for other factors that could affect fuel consumption in Canadian provinces so it is not clear how much weight to put on these results.

I next present some regressions on annual province level carbon dioxide emissions over the time period 1990 – 2016. I present difference-in-difference regressions for a BC carbon tax treatment relative to provinces and territories that have not implemented some form of carbon pricing as well as regressions with carbon prices for the carbon pricing schemes in British Columbia, Quebec, and Alberta. Alberta imposed a price on emissions in July 2007 called the Specified Gas Emitters Regulation (SGER). In effect, it is a carbon intensity cap and trade program (Leach (2012)). Quebec implemented a modest cap and trade program in 2013.

Before running regressions, it is worth noting that while British Columbia is a moderately large source of CO_2 emissions in Canada in 2007 (Figure 2A), it is a small emitter on a per capita basis (Figure 2B) or per dollar of GDP (Figure 2C). It is perhaps not surprising that three of the four provinces that have moved forward with carbon pricing schemes (British Columbia (2008), Quebec (2013), and Ontario (2017)) have very low emissions per capita or low emissions intensity. Alberta, on the other hand, is a top emitter on nearly all three metrics.

Table 2 presents carbon dioxide emission regressions for provinces and territories over the time period 1990 – 2016. I include a treatment dummy for the BC carbon tax as well as controls for GDP, population and trade. For the latter I include an export index variable that measures the price of goods exported from each province, weighted by province level exports. All regressions include province and year fixed effects.

The first regression includes all provinces and territories and finds a treatment effect of -3.6 percent, albeit imprecisely estimated. This is likely to be biased upward as I'm including provinces in the control group that have put a price on carbon. In column 2, I exclude Alberta, Quebec, and Ontario. The first two provinces put a price on emissions during the control period. Ontario is excluded as it has an ambitious feed-in tariff for renewable energy (enacted in 2009) that is unique among Canadian provinces.[57] Dropping these three provinces increases the impact of the BC carbon tax. Now emissions fall in the post-tax period by 6.6 percent. If I limit the regression period to 1995 – 2016, the impact is even larger (column 3). Columns 4 and 5 run the regression on the log of emissions per dollar of GDP (emissions intensity). With the sample restricted to 1995 – 2016, the impact is precisely estimated at the one percent level.

Table 3 provides results where carbon prices for Alberta, Quebec, and British Columbia are included.[58] The coefficient on the tax rate variable is consistently negative across the regressions but only statistically significant when the time frame is limited to 1995 – 2016. Focusing on the coefficient in column 2, a $30 carbon tax (British Columbia's rate in 2012) reduces emissions by 7.8 percent, a result consistent with the results in Table 2.

While the regression results in Tables 2 and 3 are not precisely estimated across the board, they tell a consistent story of the tax reducing emissions in British Columbia between 5 and 8 percent since the tax went into effect in 2008.

2. GDP

[57] Ontario's feed-in tariff and other provincial programs for renewable energy are described in Zacher and Reed (2011)

[58] Quebec's rate is CA$3.50 starting in 2007. A cap and trade system goes into effect in 2013 and I include average allowance auction prices for each year. Alberta enacts the SGER in 2007 at a rate of $15 per ton.

Table 4 reports similar regressions with ln(GDP) as the dependent variable. Unlike the emission regressions, I also consider variables that measure the composition of economic activity in provinces and territories. Specifically, I include the share of workers in the employment categories of manufacturing, professional, public sector, and natural resources.[59] Regressions include province fixed effects. Rather than year fixed effects, I include Canadian GDP (in logs) to control for business cycle impacts at the national level. Column (1) does not include the economy composition variables and the estimated coefficient on the carbon tax treatment variable is negative though economically small (-0.22 percent) and imprecisely estimated. The coefficient turns positive and is both economically and statistically significant when the composition variables are included. Columns 3 and 4 exclude Alberta, Quebec, and Ontario. When regressions are run over the 1990-2016 period, the estimated change in GDP is 9.2 percent and significant at the 10 percent level. When the regression is limited to 1995-2016, the coefficient falls to 7.88 percent and just misses being statistically significant at the 10 percent level.

Table 5 repeats regressions with the carbon tax rate for all provinces with carbon pricing in effect. The coefficients on the tax rate are not statistically significant but tell a similar story as in Table 4. A $30 carbon tax is associated with a roughly 6 percent increase in GDP.[60] These GDP results are consistent with simpler regressions run in Metcalf (2016). He found results that were an order of magnitude smaller, however. Given the imprecise estimates, we should not lean too heavily on these results. But it seems fair to say that GDP has not been adversely affected by the carbon tax. A couple of factors about the BC carbon tax support this result. First, the tax was designed to be revenue neutral with some of the revenue used to lower personal and business tax rates. This should enhance the efficiency of the provincial economy and could positively impact growth. Second, some of the revenue

[59] Natural resources includes forestry, fishing, mining, quarrying, oil, and gas. I do not include these share variables in the emission regressions as I would expect the carbon tax to reduce emissions, in part, by shifting the composition of economic activity.
[60] These regressions suggest the BC carbon tax led to higher GDP. Regressions not reported here suggest that the tax may have raised the growth rate of BC GDP by as much as one percent.

was specifically directed to lower-income households. To the extent these households have higher marginal propensities to consume out of income, this could, as well, support economic growth in the short run.

3. Employment

As part of their analysis of the UK CCL, Martin, de Preux, and Wagner (2014) found that the climate levy was associated with an increase in employment though imprecisely estimated. They conclude that a factor substitution effect (labor for energy) was driving the employment increase in UK manufacturing.

Yamazaki (2017) constructs employment data on 68 industries across Canadian provinces and territories for the years 2001 – 2013 to investigate the British Columbia carbon tax's impact on employment. Yamazaki notes that the carbon tax could affect employment by driving up costs and discouraging production and hence employment (output effect). The tax redistribution deriving from how carbon tax revenues are returned to businesses and households could stimulate demand for products and hence workers (redistribution effect). Finally, employment could rise (fall) if labor is a substitute (complement) for energy (factor substitution effect). His study focuses on the first two channels of employment impacts. He finds that the output effect dampens employment while the redistribution effect enhances employment. In the aggregate, he finds a modest but statistically significant impact on employment on the order of three-quarters of a percent annually. Jobs are shifting, however, from carbon and trade sensitive sectors to sectors less carbon and trade sensitive. Chemical manufacturing, for example, has the largest decline in employment while health care has the largest increase.

4. Distributional Outcomes

Numerous distributional analyses have been done of a carbon tax for the United States. Distributional impacts arise from differential consumption of carbon intensive goods whose prices have gone up relative to the general price index versus carbon light goods whose process have fallen relative to the general price index. This is the *uses side* impact and numerous studies have shown that this distributional channel is regressive. The tax also can lower factor prices. If returns to capital fall more than wages, then the carbon tax will have a progressive aspect on the *sources side*. Another factor contributing to progressivity on the sources side is the existence of indexed transfers which are disproportionately important for lower income households.[61] Goulder et al. (2018) show in a CGE analysis that the source side impacts fully offset the use side impacts so that the carbon tax, ignoring the use of revenue, is distributionally neutral to slightly progressive.

Metcalf (1999) and many others have argued that one should focus on the distributional impacts of a carbon tax reform, by which I mean the package of a carbon tax and the use of the proceeds, whether it be new spending, tax cuts, or cash grants to households. Distribution of the carbon revenue through an equal per capita cash grant as proposed by, for example, the Climate Leadership Council, would be highly progressive. Distributional tables from a recent U.S. Treasury research paper (Horowitz et al. (2017)) illustrate this. Figure 3A shows the carbon tax ignoring the use of revenue. The Treasury analysis finds it is progressive up through the 7th and 8th decile. It then turns regressive in the top deciles. With the equal per-capita rebate (figure 3B), the tax reform is sharply progressive. In fact, households up thorugh the seventieth percentile are better off in the sense of receiving more in the rebate than the impacts on disposable income through source and use side effects. Note, however, that these graphs are showing average distributional impacts at each decile. Various authors have noted that there can be considerable heterogeneity within a decile (Rausch, Metcalf, and Reilly (2011) and Cronin, Fullerton, and Sexton (2017), among others).

VI. Policy Thoughts

[61] Rausch, Metcalf, and Reilly (2011) and Goulder et al. (2018), among others, have argued that use-side regressive impacts are offset by progressive source-side impacts. Transfers are also important in explaining the source-side progressive impacts. Fullerton, Heutel, and Metcalf (2011) also stress the importance of transfers.

I don't address the details of how one would implement a carbon tax in this paper. That topic has been covered elsewhere by Metcalf and Weisbach (2009), Metcalf (2017), and Horowitz et al. (2017), among others. In brief, an excise tax on coal, natural gas, and petroleum products can piggy-back on existing fuel excise taxes (for petroleum and coal). Additional process emissions can easily be taxed such that roughly 90 percent of domestic greenhouse gas emissions (excluding forestry and land-use changes) can be included in the tax base (see Metcalf and Weisbach, 2009, for further discussion).

Two design points are worth mentioning. First, any emissions captured and permanently stored should not be taxed. Depending on the locus of taxation, those emissions can either be excluded from the tax or a rebate of the tax paid at a previous stage of production provided to anyone engaging in approved capture and sequestration techniques.

Second, a federal carbon tax will have to consider whether and how to tax imported emissions (and how to treat exports of carbon intensive goods). Ideally, we would tax the carbon content of all imports and exempt from taxation the carbon content of all exports. Doing so would tax emissions associated with domestic consumption. Taxing fossil fuel imports (and rebating the tax on exports) is straightforward and should be part of the tax design. Taxing the embedded carbon dioxide in imported goods and services is more difficult. Gray and Metcalf (2017) document that roughly 95 percent of the value of manufacturing shipments has very low carbon content. We need only concern ourselves with a handful of carbon intensive intermediate and final goods. Determining the carbon content of selected imports is a non-trivial task and Metcalf and Weisbach (2009) propose setting the tax on the basis of the emissions content of like-domestically produced carbon intensive goods.

A carbon tax addresses the central problem of climate change that the social cost of burning fossil fuels exceeds the private, market cost. A tax is the most flexible way to get millions of economic agents to adjust their behavior in large and small ways to reduce emissions. While pricing our carbon pollution is a necessary element in a cost-effective climate policy, it is not a sufficient policy for a number of reasons. Other market failures, the existence of greenhouse gas pollutants not amenable to taxation, and institutional barriers suggest the need for a suite of policies.

As discussed in the Introduction, our transition to a zero-carbon economy will require new inventions and production processes. Research and development (R&D) will be key to the successful development and diffusion of these technologies. Information and new knowledge is a pure public good that is underprovided in a market economy. A carbon tax should be complimented by a major increase in zero-carbon energy research to help develop cost-effective replacements for fossil fuels.

In addition, various regulatory and other institutional barriers impede the transition to a zero-carbon economy. Resistance by states to interstate transmission lines passing through their state can limit the use of zero-carbon electricity (wind from the Midwest or hydropower from Canada, for example).[62] The lack of clear legal and financial liability rules for carbon capture and sequestration will also impede the growth of this technology when and if it becomes cost competitive.[63]

While these other issues are important, putting a price on carbon pollution is central to any effective national policy. How do we overcome the political hurdles and get a carbon tax enacted? It will require strong political leadership. It may be that a framework for reform can also help. A powerful disciplining device for the Tax Reform Act of 1986 was the clear set of guidelines laid out by Ronald Reagan in his 1984 State of the Union Address where he called for a tax reform that simultaneously lowered tax rates while maintaining revenue neutrality. A similar set of guidelines – or a policy framework – would be useful for a carbon tax reform. My policy framework for a national carbon tax includes: 1) revenue neutrality; 2) focus on fairness; 3) streamlined policy; and 4) significant emission reductions.

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[62] Joskow and Tirole (2005) point out other barriers and market failures that lead to suboptimal investment in transmission lines.

[63] National Academies of Sciences (2018) lays out a research agenda to address the various barriers and high costs of carbon capture and storage.

Revenue neutrality ensures that long-contentious partisan differences over the size of the federal budget should not be allowed to affect the climate policy debate. A revenue neutral carbon tax reform disentangles these two issues and may ensure greater bipartisan support for a carbon tax.

Because energy makes up a more significant share of the budget of low-income families than higher-income families, many worry about a carbon tax's impact on poorer households. Tax reform packages can be designed to offset any regressive impact on lower income households. One could take the approach of the Climate Leadership Council's tax and dividend approach and rebate all of the revenue to U.S. families. This would have bipartisan appeal. But a carbon tax plan can achieve fairness without necessarily giving *all* the revenue back through a dividend scheme. A portion of the revenue could go to low and moderate income households to offset higher energy bills while the remainder could be used to lower income tax rates. Lowering tax rates would disproportionately benefit higher income households and so ensure benefits across the entire income distribution. Using revenue to lower tax rates also increases the efficiency of our economy by reducing disincentives to work or save.

There is another aspect to fairness. How should we treat workers in industries that are disproportionately affected by the shift to a zero-carbon economy? Nearly one-quarter of all U.S. coal miners work in West Virginia. Kentucky adds another fifteen percent of all coal mining jobs. No other state comes close to the number of coal miners in these two states. If we focus on a state's dependence on coal rather than on the absolute number of jobs, West Virginia and Wyoming stand out. They have the highest share of employees working in coal mining and diversifying each state's economy to become less dependent on coal would benefit the economies of these states. A national carbon tax proposal should also consider how economic development programs could help coal-dependent regions transition to a post-coal economy.

A carbon tax allows us to eliminate many energy-related tax breaks starting with tax preferences for oil and gas production in the United States. These cost roughly $4 billion a year (Metcalf (2018)) and run counter to good environmental and climate policy. Next, we can remove various investment and production tax credits for renewable energy projects. These tax preferences only make sense to support renewable energy investment and production if we can't tax carbon pollution. The existing tax breaks are a way to level the playing field between carbon polluting fuels and carbon free fuels. If we can't raise the cost of the polluting fuel, then the next best thing is to lower the cost of the non-polluting fuel. But if we enact a carbon tax, a reasonable bargain is to eliminate those tax preferences for a savings of roughly $3 billion a year.

Next consider the Clean Air Act and the endangerment finding that carbon dioxide should be regulated under the act. While the idea of replacing an inefficient regulatory approach with an efficient pricing mechanism is appealing, the Clean Air Act has been a powerful tool for improving environmental quality in this country over the past half-century. Simply giving up Clean Air Act oversight of carbon pollution is asking quite a bit given the potential for Congress to pass a carbon tax today only to have a future Congress repeal the tax. The challenge is to construct a carbon tax that provides the assurances that we will meet environmental goals over the course of this century.

One way forward is to preserve EPA regulatory authority over greenhouse gas emissions but suspend any regulatory action for emissions covered by a carbon tax so long as demonstrable progress in reducing emissions is being made. That, of course, requires that we define "progress." Progress could be measured as a target reduction in emissions relative to a given base year (e.g. 2005 emissions) at various milestone years between now and 2050. Failure to hit the targeted emission reductions would automatically trigger resumption of the EPA regulatory process under the Clean Air Act. An independent commission or advisory group established under law could oversee progress towards the emission reductions. In addition, the carbon tax could be designed such that the tax rate automatically adjusts over time to keep the United States on target to reach long-run emission reduction goals.[64]

This is not to argue that *all* greenhouse gas regulations should be put on hold. It is not realistic to subject all greenhouse gas emissions to a carbon tax. Some emissions are simply too hard to measure. A good example is methane emissions associated with fossil fuel extraction. Methane is a potent greenhouse gas with a short run impact on the environment some thirty times that of carbon dioxide. When underground coal mining was the dominant source of coal in the United States, coalbed methane was a major source of greenhouse gas emissions. Now with the shift to surface coal, methane emissions are more associated with oil and natural gas fracking. These emissions are hard to measure and are found at nearly every drill site to some extent. Rather than try to measure and tax these emissions, it makes more sense to put strong regulations in place that require state-of-the-art drilling and extraction techniques and equipment be used to minimize methane leaks. That would be coupled with strong monitoring and enforcement. Similarly, agricultural and land use emissions are difficult to tax and so more suitable to regulation.

In summary, we need to avoid a "bait and switch" where regulatory oversight over greenhouse gases is traded for a carbon tax only to find Congress does not have the will to set a sufficiently high tax to make a significant dent in emissions. Many environmentalists are already mistrustful of a carbon tax and it will be important to bring them on board in order to get Congress to act. This leads to my last framework principle. The policy must significantly cut emissions.

It will not do to set a carbon tax at $25 a ton and simply let it rise at the rate of inflation over time. It is impossible to say exactly what tax rate is required to achieve a particular emissions target. Much depends on technological advancement and consumer behavior. However technology advances,

[64] Hafstead, Metcalf, and Williams (2017) and Metcalf (forthcoming) lay out the idea of a self-adjusting carbon tax to hit emission targets.

it is likely we'll need a robust carbon price. The 2014 Stanford EMF modeling exercise found that a fifty percent reduction in U.S. emissions by 2050 would require a carbon price between $10 and $60 per ton of carbon dioxide in 2020 (looking across the bulk of models and technology assumptions) and between $100 and $300 in 2050. While the international climate negotiations have focused on a target of an eighty percent emissions reduction by 2050 from 2005 levels, most research suggests that this will be extremely expensive. The Stanford modeling study corroborates that. The participating modelers estimate that the 2050 price on carbon dioxide required to hit that target would be somewhere in the range of $200 to over $500 a ton, depending on model assumptions. [65]

What carbon price will be needed to reach any future emissions target will depend in large measure on the pace of clean energy technological development. A substantial price on carbon dioxide emissions will help spur that development. Given the very high (and probably politically unacceptable) cost of an eighty percent emissions reduction, a more modest but still aggressive goal of emission reductions between now and 2050 may be advisable. One approach would be to set a target for 2035 combined with an assessment beginning in 2030 to set a subsequent target for 2050. A 2035 target of a forty-five percent reduction in carbon dioxide emissions (relative to 2005 levels), for example, would be ambitious but within reach. A subsequent target could be set for 2050, perhaps somewhere in the sixty to eighty percent range of emissions reduction by 2050 with the precise target set as new information emerges over the first fifteen years about the damages from greenhouse gas emissions as well as clean energy technology costs.[66]

Any target set out in carbon tax legislation could be conditioned on OECD countries also committing to that goal within a short time frame and the major non-OECD emitting countries

[65] The Stanford Energy Modeling Forum exercise (EMF 24) is described in Clarke et al. (2014).
[66] Metcalf (forthcoming) discusses the use of sequential targets for a carbon tax and proposes a forty-five percent reduction by 2035 that would be consistent with a sixty percent reduction target by 2050. If clean energy technology costs fall more rapidly than expected, the 2050 target could be strengthened when set in the mid-2030s.

committing to that goal within, say, a decade. This could be combined with the Nordhaus (2015) "climate club" idea. Developed countries (or any group of major countries, for that matter) could band together and impose trade sanctions on countries that do not take effective action to reduce emissions.[67]

Once the goal is set, the carbon tax should contain a mechanism for adjustment to ensure the target is met. One simple way to do that is to enact a carbon tax with an initial tax rate (say $40 a ton of carbon dioxide emissions). The legislation would also include a clear and transparent rule for adjusting the tax rate over time to hit emission reduction benchmarks, also set out in the legislation. This would provide greater assurance that the United States would hit desired emission reduction targets while still providing the price predictability that the business community needs.[68]

The tax should also be designed so that there is the political will to sustain high tax rates on emissions. Ted Halstead, CEO of the Climate Leadership Council, has argued that the rebate in the CLC's tax and dividend plan will build political support for high tax rates since, as tax rates rise, so would rebates. Halstead may or may not be right but he is focusing on the right question: how to build political will for the changes to our energy system necessary to move to a zero emissions economy.

VII. Conclusion

A carbon tax is a cost-effective policy tool to reduce U.S. greenhouse gas emissions. It would be easy to implement, easy to administer, and straightforward for firms to comply. With twenty-seven carbon taxes in place around the world, a carbon tax is moving from a theoretical fancy of economists to a political reality. The politics around enacting a carbon tax continue to be challenging but it is

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[67] Nordhaus argues that non-participating countries could be punished with carbon tariffs or a uniform tariff on all imported goods to club members. He finds that a modest uniform tariff is more effective at promoting club membership than a carbon tariff. How Nordhaus's club idea would dovetail with the existing international trade order overseen by the World Trade Organization is unclear.

[68] This rate adjustment mechanism is set out in a proposal in Metcalf (forthcoming). His proposal builds on work by Hafstead, Metcalf, and Williams (2017). Other approaches to ensuring greater certainty of given emissions reduction targets are proposed by Aldy (2017, forthcoming) and Murray, Pizer, and Reichert (2017)

encouraging that bipartisan support for a carbon tax is growing. While a carbon tax will entail costs to the economy – after all, we cannot clean up the environment for free – evidence from other countries indicates that a carbon tax need not impose large costs on an economy. The evidence from British Columbia suggests, in fact, that a well-designed carbon tax can actually boost jobs and GDP while reducing carbon emissions.

Table 1. Swiss Carbon Tax

Tax Rate (CHF)	Enactment Date	Trigger for Tax Rate Increase
12	2008	Not applicable
36	2010	Not applicable
60	2014	• Tax rises to 60 CHF if emissions exceed 79 percent of 1990 emissions in 2012
84	2016	• Tax rises to 72 CHF if emissions exceed 76 percent of 1990 emissions in 2014 • Tax rises to 84 CHF if emissions exceed 78 percent of 1990 emissions 2014
96	2018	• Tax rises to 96 CHF if emissions exceed 73 percent of 1990 emissions 2016 • Tax rises to 120 CHF if emissions exceed 78 percent of 1990 emissions in 2016

All tax rate changes go into effect at beginning of year.

Source: International Energy Agency (2018a) and Swiss Carbon Tax Ordinance

Table 2: Carbon Dioxide Emission Regressions:
BC Difference-in-Difference

	(1)	(2)	(3)	(4)	(5)
BC Treatment	-0.036	-0.066*	-0.088***	-0.057*	-0.073***
	(0.024)	(0.036)	(0.026)	(0.027)	(0.022)
GDP	0.624***	0.565***	0.419**	--	
	(0.147)	(0.151)	(0.173)		
Population	0.275	0.491	1.114*	0.178	0.420
	(0.164)	(0.316)	(0.586)	(0.221)	(0.420)
Export Price	0.001*	0.002	0.001	0.002*	-0.002
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Constant	-1.089	-3.317	-9.779	3.608	-6.651
	(2.351)	(4.281)	(6.901)	(2.871)	(5.398)
Provinces and Territories	All	Exclude AL, ON, QC	Exclude AL, ON, QC	Exclude AL, ON, QC	Exclude AL, ON, QC
Years	1990-2016	1990-2016	1995-2016	1990-2016	1995-2016
Observations	360	279	234	279	234
R-squared	0.998	0.996	0.996	0.939	0.9981

All regressions include province and year fixed effects. Dependent variable is ln(carbon dioxide emissions). GDP and population are in logs. Regressions (4) and (5) have the ln of carbon dioxide per dollar of GDP as the dependent variable. Standard errors in parentheses are clustered at the province level.
*** p<0.01, ** p<0.05, * p<0.1

Table 3: Carbon Dioxide Emission Regressions:
Tax Rate Regressions

	(1)	(2)	(3)	(4)	(5)
Carbon Tax Rate	-0.0013	-0.0026	-0.0035*	-0.0022	-0.0028**
	(0.0021)	(0.0018)	(0.0017)	(0.0014)	(0.0013)
GDP	0.6230***	0.5697***	0.4536***	--	--
	(0.1465)	(0.1354)	(0.1482)		
Population	0.3017	0.4388**	0.8490**	0.1307	0.3540
	(0.1972)	(0.1816)	(0.3213)	(0.1129)	(0.2173)
Export Price	0.0014*	0.0014*	0.0009	0.0017*	0.0014
	(0.0007)	(0.0007)	(0.0008)	(0.0008)	(0.0009)
Constant	-1.4332	-2.6635	-6.8224	-3.0303*	-5.9313*
	(2.5907)	(2.3637)	(3.9806)	(1.4842)	(2.8518)
Provinces and Territories	All	Excludes ON	Excludes ON	Excludes ON	Exclude ON
Years	1990-2016	1990-2016	1995-2016	1990-2016	1995-2016
Observations	360	333	278	333	278
R-squared	0.998	0.997	0.998	0.958	0.957

All regressions include province and year fixed effects. Dependent variable is ln(carbon dioxide emissions). GDP and population are in logs. Regressions (4) and (5) have the ln of carbon dioxide per dollar of GDP as the dependent variable. Standard errors in parentheses are clustered at the province level.
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 4. GDP Regressions
BC Difference-in-Difference

	(1)	(2)	(3)	(4)
BC Treatment	-0.0022	0.0416**	0.0923*	0.0788
	(0.0179)	(0.0144)	(0.0431)	(0.0447)
Canadian GDP	0.8422***	0.8541***	0.8969***	0.8844***
	(0.1044)	(0.0859)	(0.0813)	(0.1426)
Population	0.6153**	0.3987*	0.0615	0.1089
	(0.2645)	(0.2169)	(0.3094)	(0.5356)
Export Price	-0.0007	0.0009	0.0010	0.0011
	(0.0007)	(0.0008)	(0.0009)	(0.0009)
Manufacturing		0.2974	0.2869	0.1756
Share		(0.3736)	(0.6240)	(0.6226)
Professional		-1.4859	-2.5594	-2.7270
Share		(1.0505)	(1.4941)	(1.6554)
Public Sector		-0.7057	-0.0253	-1.1626
Share		(0.8856)	(0.9117)	(0.8190)
Natural Resources		0.9055	0.1708	0.0537
Share		(1.5229)	(1.2507)	(1.4702)
Constant	-9.8283***	-6.7350**	-3.1841	-3.5480
	(2.3458)	(2.3089)	(3.4390)	(5.4709)
Provinces and Territories	All	Provinces Only	Provinces less AB, QC, ON	Provinces less AB, QC, ON
Years	1990-2016	1990-2016	1990-2016	1995-2016
Observations	360	270	189	154
R-Squared	0.999	0.999	0.999	0.999

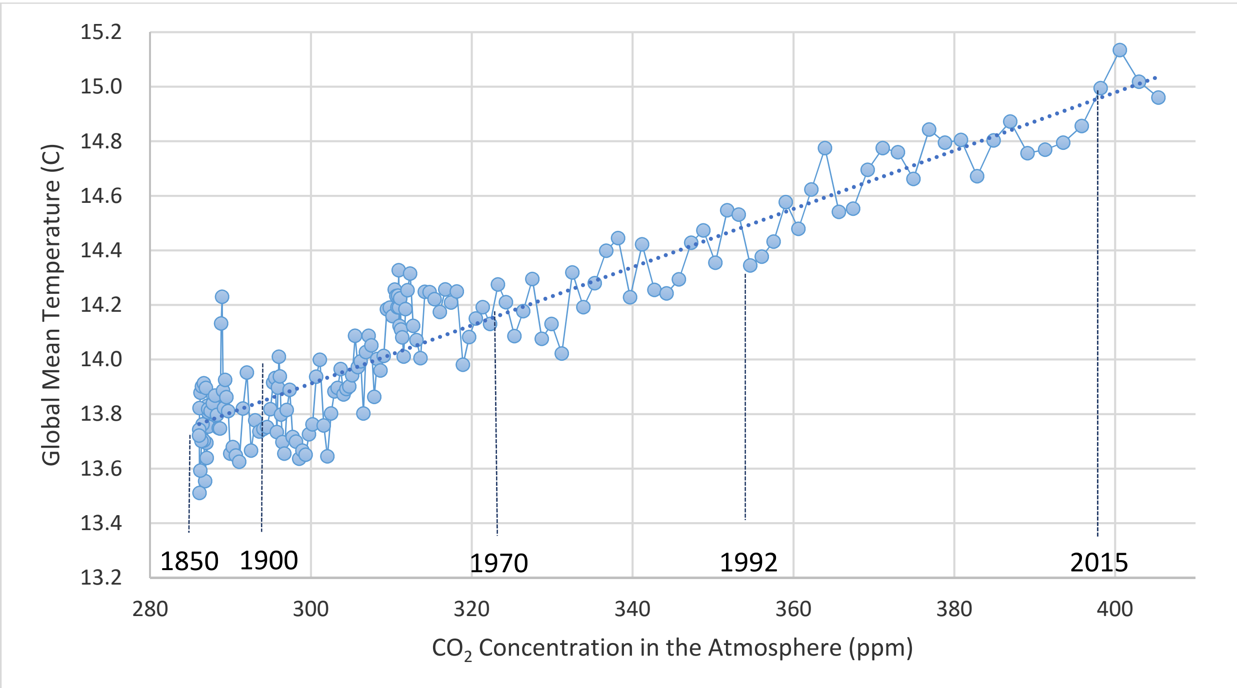
All regressions include province fixed effects. Dependent variable is ln(GDP). Canadian GDP and population are in logs. Standard errors in parentheses are clustered at the province level.
*** p<0.01, ** p<0.05, * p<0.1

Table 5. GDP Regressions
Tax Rate Regressions

	(1)	(2)	(3)	(4)
Carbon Tax Rate	-0.0005	0.0018*	0.0024	0.0022
	(0.0015)	(0.0009)	(0.0014)	(0.0013)
Canadian GDP	0.8406***	0.8625***	0.8540***	0.8802***
	(0.1067)	(0.0847)	(0.0835)	(0.1099)
Population	0.6294*	0.3600	0.3167	0.3185
	(0.2920)	(0.2246)	(0.2516)	(0.2970)
Export Price	-0.0006	0.0009	0.0011	0.0010
	(0.0007)	(0.0008)	(0.0009)	(0.0009)
Manufacturing		0.3312	0.4136	0.3205
Share		(0.3599)	(0.4239)	(0.3648)
Professional		-1.6006	-1.7846	-2.3823*
Share		(1.0612)	(1.1229)	(1.2465)
Public Sector		-0.6915	-0.6474	-1.1353
Share		(0.8879)	(0.9814)	(0.6643)
Natural Resources		0.7830	0.6903	0.4506
Share		(1.4176)	(1.4094)	(1.3736)
Constant	-9.9960***	-6.2940**	-5.7433*	-6.0458*
	(2.6875)	(2.4443)	(2.8014)	(2.8513)
Provinces and Territories	All	Provinces Only	Provinces less ON	Provinces less ON
Years	1990-2016	1990-2016	1990-2016	1995-2016
Observations	360	270	243	220
R-Squared	0.999	0.999	0.999	0.999

All regressions include province fixed effects. Dependent variable is ln(GDP). Canadian GDP and population are in logs. Standard errors in parentheses are clustered at the province level.
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Figure 1 – Carbon Dioxide Concentrations and Temperature



Source: see text

Figure 2A – 2007 Provincial CO_2 Emissions

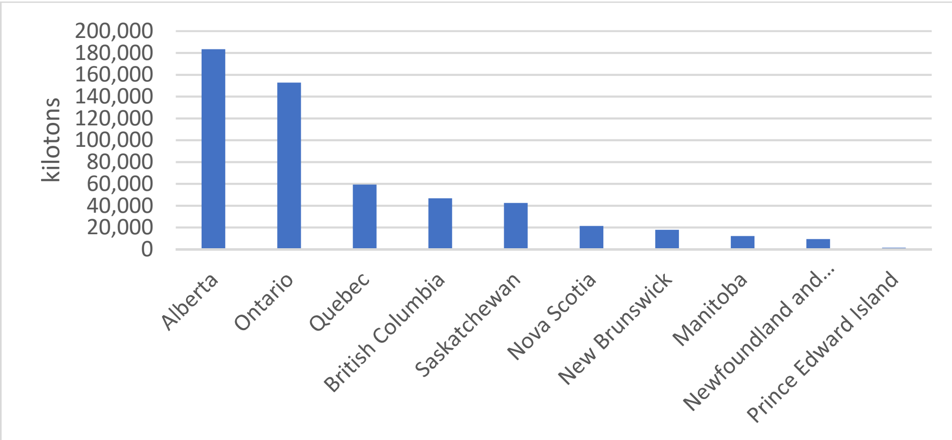


Figure 2B – 2007 Provincial Per Capita Emissions

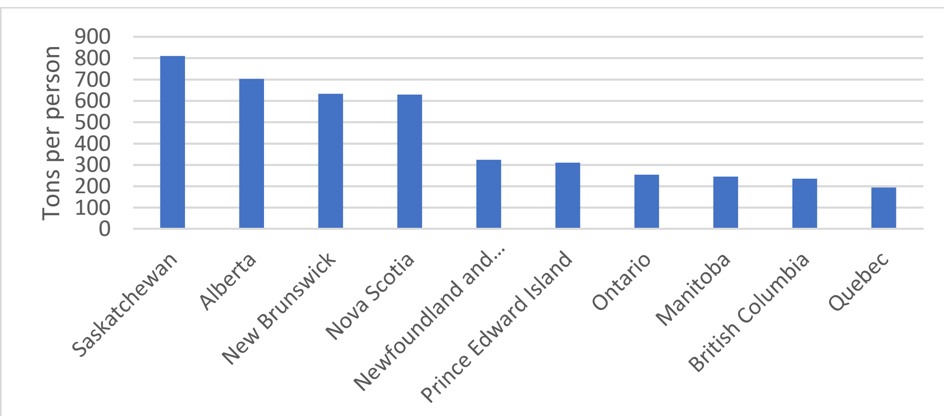


Figure 2C – 2007 Provincial Emissions Intensity

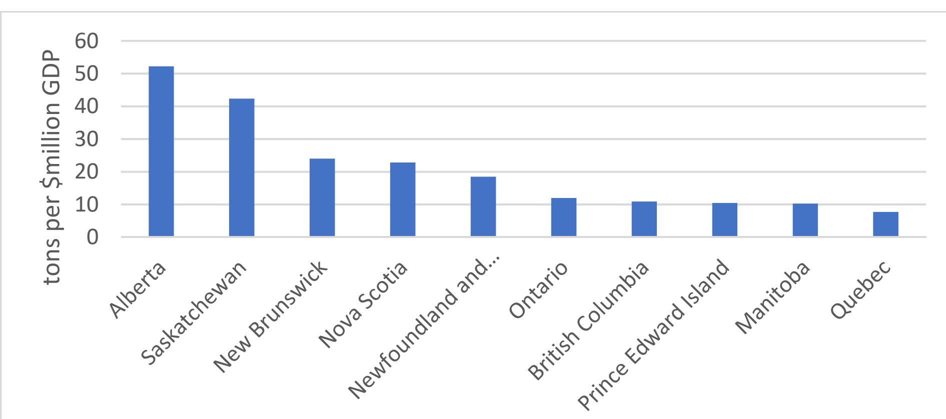
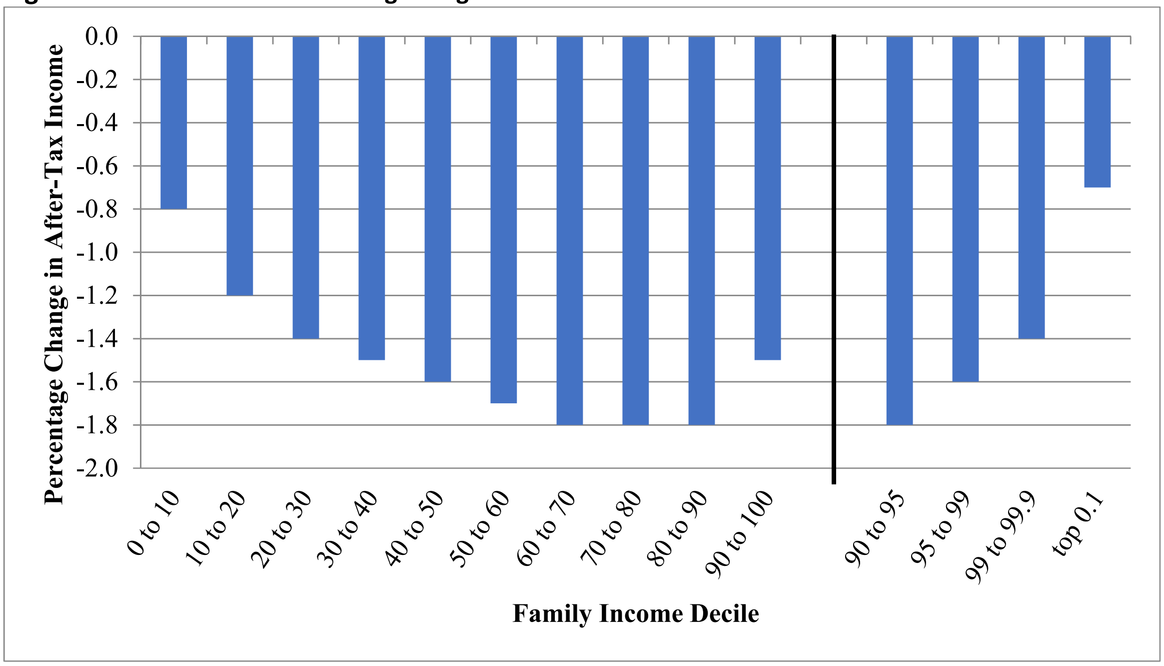
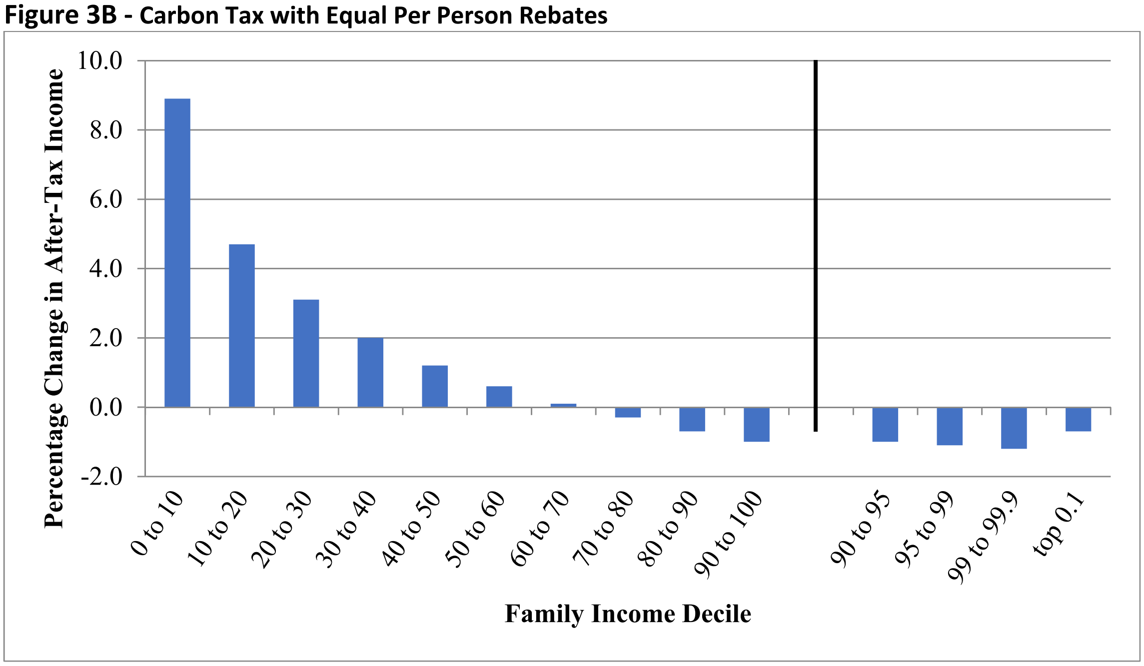


Figure 3A - Carbon Tax Burden – Ignoring Use of Revenue



Source: U.S. Department of the Treasury (2017)

Figure 3B - Carbon Tax with Equal Per Person Rebates



Source: U.S. Department of the Treasury (2017)

References

Acemoglu, Daron, Philippe Aghion, Leonardo Bursztyn, and David Hemous. 2012. "The Environment and Directed Technical Change." *American Economic Review* 102 (1):131-166.

Acemoglu, Daron, Ufuk Akcigit, Douglas Hanley, and William Kerr. 2016. "Transition to Clean Technology." *Journal of Political Economy* 124 (1):52-104.

Aldy, Joseph E. 2017. "Designing and Updating a U.S. Carbon Tax in an Uncertain World." *Harvard Environmental Law Review* 41:28-40.

Aldy, Joseph E. forthcoming. "Carbon Tax Review and Updating." *Review of Environmental Economics and Policy* xx (xx):xx-xx.

Allcott, Hunt, and Todd Rogers. 2014. "The Short-Run and Long-Run Effects fo Behavioral Interventions: Experimental Evidence from Energy Conservation." *American Economic Review* 104 (10):3003-3037.

Anderson, Soren T., and James M. Sallee. 2016. "Designing Policies to Make Cars Greener." *Annual Review of Resource Economics* 8:157-180.

Barron, Alexander R., Allen A. Fawcett, Marc A. C. Hafstead, James McFarland, and Adele C. Morris. 2018. "Policy Insights From the EMF 32 Study on U.S. Carbon Tax Scenarios." *Climate Change Economics* 9 (1):1-47. doi: https://doi.org/10.1142/S201000781840002X.

Boomhower, Judson, and Lucas W. Davis. 2014. "A Credible Approach for Measuring Inframarginal Participation in Energy Efficiency Programs." *Journal of Public Economics* 113:67-79.

Borenstein, Severin, and Lucas W. Davis. 2016. "The Distributional Effects of U.S. Clean Energy Tax Credits." In *Tax Policy and the Economy*, edited by Jeffrey Brown. Chicago: University of Chicago Press.

Bovenberg, A. Lans, and Ruud A. de Mooij. 1994. "Environmental Levies and Distortionary taxation." *American Economic Review* 84:1085-.

Bovenberg, A. Lans, and Lawrence H. Goulder. 1996. "Optimal Environmental Taxation in the Presence of Other Taxes: General Equilibrium Analysis." *American Economic Review* 86 (4):985-1000.

Bovenberg, A. Lans, and Lawrence H. Goulder. 2002. "Environmental Taxation and Regulation." In, edited by Alan J. Auerbach and Martin eds Feldstein, 1471-1545. Handbooks in Economics, vol. 3. Amsterdam; London and New York: Elsevier Science, North-Holland.

Brannlund, Runar, Tommy Lundgren, and Per-Olov Marklund. 2014. "Carbon Intensity in Production and the Effects of Climate Policy - Evidence from Swedish Industry." *Energy Policy* 67:844-857.

Bruvoll, Annegrete, and Bodil Merethe Larsen. 2004. "Greenhouse Gas Emissions in Norway: Do Carbon Taxes Work?" *Energy Policy* 32:493-505.

Burtraw, Dallas, and Amelia Keyes. 2018. "Recognizing Gravity as a Strong Force in Atmosphere Emissions Markets." *Agricultural and Resource Economics Review* 47 (2):201-219.

Bushnell, James B., Stephen P. Holland, Jonathan E. Hughes, and Christopher R. Knittel. 2017. "Strategic Policy Choice in State-Level Regulation: The EPA's Clean Power Plan." *American Economic Journal: Economic Policy* 9 (2):57-90. doi: 10.1257/pol.20150237.

Carl, Jeremy, and David Fedor. 2016. "Tracking Global Carbon Revenues: A Survey of Carbon Taxes versus Cap-and-Trade in the Real World." *Energy Policy* 96:50-77.

Carlson, Curtis, Dallas Burtraw, Maureen Cropper, and Karen Palmer. 2000. "Sulfur Dioxide Control by Electric Utilities: What Are the Gains From Trade?" *Journal of Political Economy* 108 (6):1292-1326.

Carlson, Curtis, and Gilbert E. Metcalf. 2008. "Energy Tax Incentives and the Alternative Minimum Tax." *National Tax Journal* LXI (3):477-491.

Chaffin, Joshua. 2011. "Cyber-Theft Halts EU Emissions Trading." *Financial Times*, Jan. 19.

Chandra, Ambarish, Sumeet Gulati, and Milind Kandlikar. 2010. "Green Drivers or Free Riders? An Analysis of Tax Rebates for Hybrid Vehicles." *Journal of Environmental Economics and Management* 60:78-93.

Clarke, Leon E., Allen A. Fawcett, John P. Weyant, James McFarland, Vaibhav Chaturvedi, and Yuyu Zhou. 2014. "Technology and U.S. Emissions Reductions Goals: Results of the EMF 24 Modeling Exercise." *The Energy Journal* 35 (S11):9-31.

Coase, Ronald. 1960. "The Problem of Social Cost." *Journal of Law and Economics* 3:1-44.

Cronin, Julie-Anne, Don Fullerton, and Steven E. Sexton. 2017. Vertical and Horizontal Redistributions from a Carbon Tax and Rebate. Cambridge, MA: National Bureau of Economic Research.

Cullen, Joseph A., and Erin T. Mansur. 2017. "Inferring Carbon Abatement Costs in Electricity Markets: A Revealed Preference Approach Using the Shale Revolution." *American Economic Journal: Economic Policy* 9 (3):106-33.

Dales, J.H. 1968. *Pollution, Property, and Prices*. Toronto: University of Toronto Press.

Eilperin, Juliet. 2017. "EPA's Pruitt Signs Proposed Rule to Unravel Clean Power Plan." *Washington Post*, October 10.

Elgie, Stewart. 2014. British Columbia's Carbon Tax Shift: An Environmental and Economic Success. In *Development in a Changing Climate*. Washington, DC: World Bank.

Elgie, Stewart, and Jessica McClay. 2013. BC's Carbon Tax Shift After Five Years: Results. Ottawa: Sustainable Prosperity.

Ellerman, A. Denny, Paul L. Joskow, Juan-Pablo Montero, Richard Schmalensee, and Elizabeth M. Bailey. 2000. *Markets for Clean Air: The U.S. Acid Rain Program*. Cambridge: Cambridge University Press.

Fischer, Carolyn. 2010. "Renewable Portfolio Standards: When Do They Reduce Price?" *The Energy Journal* 31 (1):101-119.

Fullerton, Don, Garth Heutel, and Gilbert E. Metcalf. 2011. "Does the Indexing of Government Transfers Make Carbon Pricing Progressive?" *American Journal of Agricultural Economics* 94 (2):347-353.

Goulder, Lawrence H., Marc A. C. Hafstead, GyuRim Kim, and Xianling Long. 2018. Impacts of a Carbon Tax Across U.S. Household Income Groups: What are the Equity-Efficiency Trade-Offs? Cambridge, MA: NBER.

Gray, Wayne, and Gilbert E. Metcalf. 2017. "Carbon Tax Competitiveness Concerns: Assessing a Best Practices Income Tax Credit " *National Tax Journal* 70 (2):447-468.

Gruenspecht, Howard K. 1982. "Differentiated Regulation: The Case of Auto Emissions Standards." *American Economic Review* 72 (2):328-331.

Hafstead, Marc, Gilbert E. Metcalf, and Roberton C. Williams, III. 2017. "Adding Quantity Certainty to a Carbon Tax: The Role of a Tax Adjustment Mechanism for Policy Pre-Commitment." *Harvard Environmental Law Review* 41:41-57.

Hoel, Michael, and Larry Karp. 2002. "Taxes versus Quotas for a Stock Pollutant." *Resource and Energy Economics* 24 (4):367-384.

Horowitz, John, Julie-Anne Cronin, Hannah Hawkins, Laura Konda, and Alex Yuskavage. 2017. Methodology for Analyzing a Carbon Tax. Washington, DC: U.S. Department of the Treasury.

Houde, Sebastien, and Joseph E. Aldy. 2017. "Consumers' Response to State Energy Efficient Appliance Rebate Programs." *American Economic Journal: Economic Policy* 9 (4):227-255.

Hsiang, Solomon, Robert Kopp, Amir Jina, James Rising, Michael Delgado, Shashank Mohan, D. J. Rasmussen, Robert Muir-Wood, Paul Wilson, Michael Oppenheimer, Kate Larsen, and Trevor Houser. 2017. "Estimating economic damage from climate change in the United States." *Science* 356 (6345):1362-1369. doi: 10.1126/science.aal4369.

International Energy Agency. 2018a. Energy Prices and Taxes: Second Quarter 2018. Paris: IEA.

International Energy Agency. 2018b. The Future of Cooling. Paris: IEA.

Jacobsen, Mark R. 2013. "Evaluating US Fuel Economy Standards in a Model with Producer and Household Heterogeneity." *American Economic Journal: Economic Policy* 5 (2):148-187. doi: 10.1257/pol.5.2.148.

Joskow, Paul L., and Jean Tirole. 2005. "Merchant Transmission Investment." *Journal of Industrial Economics* 53 (2):233-264.

Kaplow, Louis. 1996. "The Optimal Supply of Public Goods and the Distortionary Cost of Taxation." *National Tax Journal* 49 (4):513-533.

Karp, Larry, and Christian Traeger. 2018. Prices Versus Quantities Reassessed. Berkeley: University of California, Berkeley.

Karp, Larry, and Jiangfeng Zhang. 2005. "Regulation of Stock Externalities with Correlated Abatement Costs." *Environmental and Resource Economics* 32 (2):273-299.

Karplus, Valerie J., Sergey Paltsev, Mustafa Babiker, and John M. Reilly. 2013. "Should a vehicle fuel economy standard be combined with an economy-wide greenhouse gas emissions constraint? Implications for energy and climate policy in the United States." *Energy Economics* 36 (C):322-333. doi: 10.1016/j.eneco.2012.09.001.

Koch, Nicolas, Sabine Fuss, Godefroy Grosjean, and Ottmar Edenhofer. 2014. "Causes of the EU ETS price drop: recession, CDM, renewable policies or a bit of everything? – New evidence." *Energy Policy* 73:676-685.

Leach, Andrew. 2012. "Policy Forum: Alberta's Specified Gas Emitters Regulation." *Canadian Tax Journal* 60 (4):881-98.

Lehane, Bill. 2011. "Hackers Steal Carbon Credits." *Prague Post*, Jan. 26.

Lewis, Mark. 2018. "EU Carbon Allowance Market to Shake its Oversupply Problem." *The Financial Times*, April 26.

Lin, Boqiang, and Xuehui Li. 2011. "The Effect of Carbon Price on Per Capita CO2 Emissions." *Energy Policy* 39:5137-5146.

Martin, Ralf, Laurie B. de Preux, and Ulrich J. Wagner. 2014. "The Impact of a Carbon Tax on Manufacturing: Evidence from Microdata." *Journal of Public Economics* 117:1-14.

McFarland, James, Allen A. Fawcett, Adele C. Morris, John M. Reilly, and Peter J. Wilconxen. 2018. "Overview of the EMF 32 Study on U.S. Carbon Tax Scenarios." *Climate Change Economics* 9 (1):1-37.

Metcalf, Gilbert E. 1999. "A Distributional Analysis of Green Tax Reforms." *National Tax Journal* 52 (4):655-681.

Metcalf, Gilbert E. 2009. "Market-based Policy Options to Control U.S. Greenhouse Gas Emissions." *Journal of Economic Perspectives* 23 (2):5-27.

Metcalf, Gilbert E. 2016. "A Conceptual Framework for Measuring the Effectiveness of Green Fiscal Reforms." *International Journal on Green Growth and Development* 2 (2):87-126.

Metcalf, Gilbert E. 2017. Implementing a Carbon Tax. Washington, DC: Resources For the Future.

Metcalf, Gilbert E. 2018. "The Tax Treatment of Oil and Gas Production in the United States: Assessing the Options." *Journal of the Association of Environmental and Resource Economists* 5 (1):1-37.

Metcalf, Gilbert E. 2019. *Paying for Pollution: Why a Carbon Tax is Good for America*. New York: Oxford University Press.

Metcalf, Gilbert E. forthcoming. "An Emissions Assurance Mechanism: Adding Environmental Certainty to a Carbon Tax." *Review of Environmental Economics and Policy*.

Metcalf, Gilbert E., and David Weisbach. 2009. "The Design of a Carbon Tax." *Harvard Environmental Law Review* 33 (2):499-556.

Murray, Brian, William A. Pizer, and Christina Reichert. 2017. "Increasing Emissions Certainty Under a Carbon Tax." *Harvard Environmental Law Review* 41:14-27.

National Academies of Sciences, Engineering, and Medicine. 2018. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. Washington DC: The National Acadamies Press.

Newell, Richard G., and William A. Pizer. 2003. "Regulating Stock Externalities Under Uncertainty." *Journal of Environmental Economics and Management* 45:416-432.

Nordhaus, William D. 2013. *The Climate Casino: Risk, Uncertainty, and Economics for a Warming World*. New Haven: Yale University Press.

Nordhaus, William D. 2015. "Climate Clubs: Overcoming Free-Riding in International Climate Policy." *American Economic Review* 105 (4):1339-1370.

Nordhaus, William D., and Andrew Moffat. 2017. A Survey of Global Impacts of Climate Change: Replication, Survey Methods, and a Statistical Analysis. Cambridge, MA: National Bureau of Economic Research.

Parry, Ian W. H. 1995. "Pollution Taxes and Revenue Recycling." *Journal of Environmental Economics and Management* 29:S64-S77.

Petit J.R., Jouzel J., Raynaud D., Barkov N.I., , Basile I. Barnola J.M., Bender M., Chappellaz J., Davis J., Delaygue G., , Kotlyakov V.M. Delmotte M., Legrand M., Lipenkov V., Lorius C., , and Ritz C. Pepin L., Saltzman E., Stievenard M. 1999. "Climate and Atmospheric History of the Past 420,000 years from the Vostok Ice Core, Antarctica." *Nature* 399:429-436. doi: 10.1038/20859.

Pigou, Arthur C. 1920. *The Economics of Welfare*. London: Weidenfeld and Nicolson.

Pindyck, Robert S. 2017. "Coase Lecture - Taxes, Targets and the Social Cost of Carbon." *Economica* 84:345-364. doi: 10.1111/ecca.12243.

Pirttila, Jukka, and Matti Tuomala. 1997. "Income Tax, Commodity Tax and Environmental Policy." *International Tax and Public Finance* 4:379-393.

Rausch, Sebastian, Gilbert E. Metcalf, and John M. Reilly. 2011. "Distributional Impacts of Carbon Pricing: A General Equilibrium Approach with Micro-Data for Households." *Energy Economics* 33:S20-S33.

Reguant, Mar. 2018. The Efficiency and Sectoral Distributional Implications of Large-Scale Renewable Policies. Cambridge: National Bureau of Economic Research.

Rivers, Nicholas, and Brandon Schaufele. 2015. "Salience of Carbon Taxes in the Gasoline Market." *Journal of Environmental Economics and Management* 74:23-36.

Sallee, James M. 2011. "The Taxation of Fuel Economy." *Tax Policy and the Economy* 25:1-37.

Schmalensee, Richard, and Robert N. Stavins. 2013. "The SO_2 Allowance Trading System: The Ironic History of a Grand Policy Experiment." *Journal of Economic Perspectives* 27 (1):103-122.

Smale, Robin, Murray Hartley, Cameron Hepburn, John Ward, and Michael Grubb. 2006. "The Impact of CO_2 Emissions Trading on Firm Profits and Market Prices." *Climate Policy* 6 (1):31-48.

Szabo, Mike. 2019. South African Carbon Tax Bill Heads for Parliament Vote After Committee Approval. In *Carbon Pulse*.

U.S. Environmental Protection Agency. 2018. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 - 2016. Washington, DC: EPA.

U.S. Interagency Working Group on the Social Cost of Carbon. 2016. Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866. edited by U.S. EPA. Washington, DC: EPA.

Wagner, Gernot, and Martin L. Weitzman. 2015. *Climate Shock: The Economic Consequences of a Hotter Planet*. Princeton: Princeton University Press.

Wald, Matthew L. 2012. "An Argument Over Wind." *The New York Times*, September 14.

Weitzman, Martin. 1974. "Prices vs. Quantities." *Review of Economic Studies* 41 (4):477-491.

Wingrove, Josh. 2019. "Carbon Tax Takes Effect in Industrial Heartland." *Climate Wire*, January 2.

World Bank Group. 2018. States and Trends of Carbon Pricing 2018. Washington DC: World Bank Group.

World Economic Forum. 2018. Global Competitiveness Report 2017 - 2018.

Yamazaki, Akio. 2017. "Jobs and Climate Policy: Evidence from British Columbia's Revenue-Neutral Carbon Tax." *Journal of Environmental Economics and Management* 83:197-216.

Zacher, Glenn, and Kurtis Reed. 2019. *Renewable Energy Regimes in Canada*, December 8 2011 [cited Feb. 23 2019]. Available from http://www.acc.com/legalresources/quickcounsel/reric.cfm.