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Source: *Brookings Papers on Economic Activity*, (SPRING 2019), pp. 405-458
Published by: Brookings Institution Press
Stable URL: https://www.jstor.org/stable/10.2307/26798825

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ABSTRACT Climate change is driven by the buildup of greenhouse gases (GHGs) in the atmosphere, which is 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 alternative approaches to reducing our GHG pollution. Carbon taxes have been implemented in 23 jurisdictions around the world. I provide evidence on emission reductions and the economic impact of British Columbia's carbon tax, a broad-based carbon assessment that has been in effect for over a decade. I also provide an analysis of carbon taxes used in the countries that belong to the European Union.

Climate change is a classic global pollution externality, with billions of polluters creating damage for billions of people. Moreover, the world's continued use of fossil fuels and other GHG-emitting activities creates damage 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. Although 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

Conflict of Interest Disclosure: The author is a professor of economics at Tufts University and a research associate at the National Bureau of Economic Research. Beyond these affiliations, the author did not receive financial support from any firm or person for this paper or from any firm or person with a financial or political interest in this paper. He is currently not an officer, director, or board member of any organization with an interest in this paper. No outside party had the right to review this paper before circulation. The views expressed in this paper are those of the author, and do not necessarily reflect those of Tufts University or the National Bureau of Economic Research.

countries taking aggressive action to curb GHGs if the United States does not enact strong policy measures 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. Although 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. And research and development (R&D) will be key to their successful diffusion—whether it is advanced battery storage, carbon capture and storage, or inexpensive, safe, and modular nuclear power. Information and new knowledge are pure public goods that are underprovided in a market economy.[1] The information market failure is a general market failure and not one specific to GHGs. But R&D is central to any solution to the GHG problem, and directed R&D support can ensure that emission reduction targets are met with lower carbon tax rates and the consequent economic costs of the tax, a point made by Daron Acemoglu and others (2012) and by Acemoglu and others (2016). These two market failures—pollution and the pure public goods nature of R&D—should drive our choice of policy. In section V, I discuss other policy needs to complement the carbon tax and energy-related R&D.

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

I. Climate Change

"Climate change" is a catchall term for the climate effects arising from accumulations of GHGs in the Earth's atmosphere. The most prominent GHG is carbon dioxide (CO_2), which accounts for over three-quarters of

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.

global emissions. Methane is the second most prominent GHG, accounting for a further almost 16 percent of global emissions. Nitrous oxides (N_2O) and other gases account for the remaining close to 8 percent of GHG emissions. CO_2 is a higher share of U.S. GHG emissions, accounting for about 82 percent, with methane accounting for about 10 percent and N_2O and other gases accounting for the remaining close to 8 percent.[2]

Focusing on sectors, about 84 percent of U.S. GHG emissions are in the energy sector. Agriculture accounts for about 9 percent, industrial processes and product use for about 6 percent, and waste for about 2 percent. Within energy, about 94 percent of emissions are from CO_2, of which about 97 percent is associated with fossil fuel combustion. Breaking down energy-related fossil fuel combustion CO_2 emissions, about 36 percent are from transportation, about 16 percent industrial, about 11 percent residential and commercial, and 36 percent from electricity.[3]

The damage 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 measures the long-run equilibrium increase in temperature arising from a change in the stock of GHGs in the atmosphere. Just as the glass roof of a greenhouse traps solar radiation and raises the temperature inside the greenhouse, CO_2 and other GHGs 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 GHGs in the long run depends on the climate sensitivity parameter.[4]

Over one hundred years ago, Sweden's Svante Arrhenius, a childhood mathematics prodigy and Nobel Prize–winning chemist, made the first estimates of climate sensitivity in his 1906 book *Worlds in the Making*.

2. These data are for 2014 and are taken from the World Resources Institute's CAIT Climate Data Explorer (cait.wri.org). Emissions of non-CO_2 gases are converted to a CO_2 equivalent using a 100-year global warming potential taken from the 1996 *Second Assessment Report* of the Intergovernmental Panel on Climate Change.

3. These are shares of total GHG emissions as reported in U.S. Environmental Protection Agency (EPA 2018, tables 2-3, 2-4, and 2-5). Shares do not account for any forest or land use sinks. 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 (about 36 percent each).

4. Equilibrium climate sensitivity measures the long-run equilibrium response. Transient climate response measures the temperature response over a shorter period. Figure 1 shows the relationship between carbon concentrations and temperature increase that reflects the transient climate response relationship.

He estimated the value of the climate sensitivity parameter to be 4 degrees Celsius—that is, a doubling of GHGs leads to an increase in temperature by 4 degrees Celsius (just over 7 degrees Fahrenheit). He made this calculation notwithstanding the very early state of climate science and the lack of current, let alone historical, data on temperature and GHG concentrations. His estimate of climate sensitivity is remarkably durable. Despite the complexity of modeling climate sensitivity, modern estimates are in the ballpark of Arrhenius's hundred-year-old estimate.

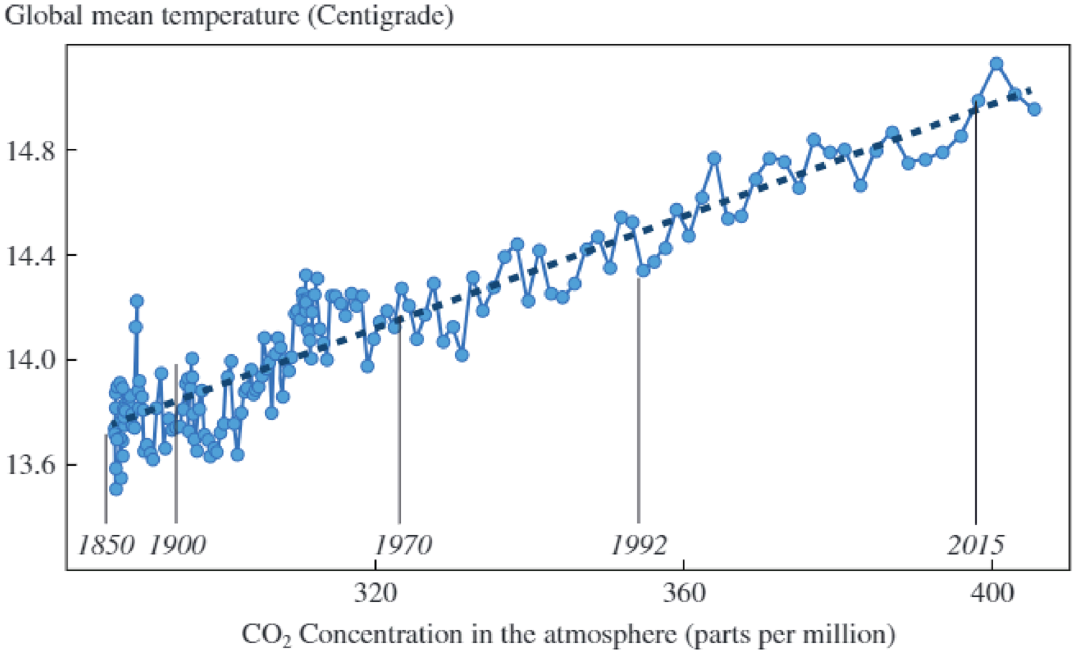
Pre–industrial era concentrations of CO_2 in the atmosphere are typically pegged at 280 parts per million, though air samples taken from Antarctic ice cores make clear that concentrations have ranged between 180 and 290 parts per million over the past 400,000 years (Petit and others 1999). Current measurements of CO_2 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, which are just over 11,000 feet above sea level. The Keeling Curve shows a dramatically rising concentration of CO_2 in the atmosphere, with current monthly average concentrations topping 405 parts per million. Figure 1 shows the relationship between atmospheric CO_2 concentrations and global mean temperatures since 1850.

The U.S. National Oceanic and Atmospheric Administration publishes its Climate Extremes Index as a way to summarize extreme temperature (high and low), precipitation, droughts, and tropical storm intensity with data going back to 1910. Six of the top 10 extreme climate years have occurred since 2005, and each of the years since 2015 has been among the top 6 extreme years.[5] This index highlights the fact that climate change is as much (if not more) about climate variability than it is about warming.

Below, I discuss the economic costs of climate policy. Any discussion of policy costs should recognize that failing to act also has costs. Although a detailed analysis is beyond the scope of this paper, a few comments are in order. Until recently, most measures of the damage from GHG emissions were derived from reduced-form damage functions embedded in integrated assessment models, such as the Nordhaus Dynamic Integrated Climate-Economy Model. William Nordhaus (2013) describes the various cost factors and models damage (as a percentage of global output) as an (approximately) quadratic function of temperature increase. In a recent

5. The data for the National Oceanic and Atmospheric Administration's Climate Extremes Index for the contiguous United States are published at https://www.ncdc.noaa.gov/extremes/cei/graph/us/cei/01-12.

Figure 1. The Relationship between Atmospheric CO_2 Concentrations and Global Mean Temperatures since 1850



Source: CO_2 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. Global mean temperatures are from Berkeley Earth, at http://berkeleyearth.lbl.gov/auto/Global/Land_and_Ocean_summary.txt. The format of this figure 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 CO_2 concentrations since 1850 yields an estimated 2.5-degree Celsius increase in temperature from a doubling of CO_2 concentrations. This regression fit is more akin to the transient climate response than the equilibrium climate sensitivity.

meta-analysis, Nordhaus and Andrew Moffat (2017) find no evidence for sharp convexities or discontinuities in the damage function, and they find damage 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, are little more than guesswork. As a result, these damage estimates should be viewed as lower bounds.

Solomon Hsiang and others (2017) construct detailed estimates of the damage from climate change in the United States at the county level, and they find that the combined market and nonmarket damage for a 1-degree C increase in temperature is on the order of 1.2 percent of GDP. Damage is unequally distributed, with higher damage 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 damage 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 damage 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 costs. 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.

II. Theory

Policymakers have a variety of instruments at their disposal to bring about a reduction in GHG emissions. They can raise the cost of emissions, lower the cost of clean alternatives to fossil fuels and other GHG sources, and impose regulations mandating specific technologies or benchmarks for emission reductions, among other options. In this section, I compare and contrast the various alternatives and argue that a carbon tax is the most cost-effective way to achieve a given reduction in GHG emissions.

II.A. Putting a Price on Pollution

Arthur Pigou is credited with the idea of using taxes to correct the market failure arising from the presence of externalities, as explained in his 1920 book *The Economics of Welfare.* The problem with pollution is that there is a divergence between the private and social costs of a good due to pollution, with the divergence equal to the marginal damage from the pollution. If this is the problem, argued Pigou, then taxing the pollution at its social marginal damage 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 is more practical. Such is not the case, however, for energy-related CO_2 emissions. The amount of CO_2 associated with burning a ton of coal, a gallon of gasoline, or a therm of natural gas is, for all intents and purposes, constant.[6] Changes

6. 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.

in industrial processes may affect the amount of fossil fuel burned but not the emissions per unit of fuel input.[7]

A Pigouvian tax is especially attractive in a situation where it is (relatively) easy to measure the marginal damage from the pollutant but where it is difficult to identify the individuals suffering the damage from pollution. In such an instance, bargaining between the polluter and those affected by pollution, à la Ronald Coase, cannot substitute for government intervention. Coase (1960, 852) 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."

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 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, which was established as part of the Clean Air Act Amendments of 1990.[8] The European Union's Emission Trading System (ETS) is the largest GHG cap-and-trade system established to date (World Bank Group 2018). The cap-and-trade concept is credited to the Canadian economist John Dales (1968) and builds on Ronald Coase's conception of the pollution problem as one of incomplete property rights (Coase 1960). By establishing a cap on pollution and distributing rights to pollute, a cap-and-trade system establishes clear (albeit limited by the cap) property rights to pollute.

7. The one major exception is carbon capture and storage, where CO_2 is captured when the fuel is burned and permanently stored to prevent its release into the atmosphere. I discuss carbon capture and storage and its treatment under a carbon tax in section V.

8. Schmalensee and Stavins (2013) provide a history and assessment of the Acid Rain Program.

An extensive literature compares and contrasts a carbon tax and a cap-and-trade policy. Although 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.[9] 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.[10]

Setting aside economic efficiency, three factors favor carbon taxes over cap-and-trade systems.[11] 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 planning long-lived, capital-intensive projects. The Acid Rain Program illustrates the potential for price volatility. Allowance prices fluctuated anywhere from zero to $1,200 in the five years between 2005 and 2010.[12] Price fluctuations are not limited to the Acid Rain Program of the U.S. Environmental Protection Agency (EPA). Allowance prices in the European Union's ETS fell by one-third in one week in April 2006 and by a further 20 percent over the next month upon release of information that initial allowance allocations had been too generous.[13]

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

9. 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 GHGs 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.

10. Carlson and others (2000) suggest that the cost of regulating sulfur dioxide emissions with a cap and trade could be reduced as much as one-half compared with traditional command-and-control regulation. See also Ellerman and others (2000).

11. I elaborate on these issues in Metcalf (2019). Goulder and Schein (2013) have a similar list.

12. See Schmalensee and Stavins (2013, figure 2).

13. The price decline is discussed in Metcalf (2009).

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. The EU commissioners noted that hackers had also broken into accounts in Austria, Poland, Greece, and Estonia and that as much as $40 million in allowances was stolen.[14] Though 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 the goal of reducing emissions. This is a big problem for cap-and-trade systems. Consider a cap set with a goal of realizing allowance prices of $40 a ton. This price target would contribute to driving innovation and the development of new carbon-free technologies that we will need to get to a zero-carbon economy by the end of the century. Investors will not place risky bets on new energy technologies that reduce emissions unless they can be confident that there is a good chance of earning a high return on this 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 will be taking. This is 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 investors for the risks they took in underwriting a new and unproven technology.

Any additional policies enacted to reduce emissions in sectors covered by the cap-and-trade program (for example, low carbon fuel standards or renewable portfolio standards) will do nothing to reduce emissions but can only undermine allowance prices in the program. Any emission reductions in these supplementary programs will simply be offset by increases in emissions elsewhere, assuming the cap is binding. All that can happen is that the allowance price falls as the cap is loosened.

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 European Union's ETS (2013–20), prices have generally ranged between $3 and $8 per ton and only broke through the

14. The cybertheft story is reported by Chaffin (2011) and Lehane (2011), among others.

$10 barrier in March 2018. Prices in the earlier trading period (2008–12) 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.[15]

To address low prices in the ETS, the EU initiated a program to reduce a surplus of allowances in the system that stemmed, 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 its Market Stability Reserve.[16] This has helped raise ETS allowance prices to their current level (as of July 2019) of about $30 a metric ton.[17]

The World Bank's 2018 annual review of carbon pricing tracks carbon pricing in roughly 40 countries and 20 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, 5 countries have carbon tax rates of at least $50 a ton, with Sweden leading the group at about $140.

The most powerful arguments 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 policymakers; and (2) allowances created in a cap-and-trade program are valuable assets that policymakers can distribute in ways to reduce political opposition. For example, the Acid Rain Program created roughly 10 million allowances in 2000. 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),

15. Allowance prices for the 2013 period forward are taken from the European Energy Exchange website (https://www.eex.com/en/market-data/environmental-markets/spot-market/european-emission-allowances). Prices from the 2008–12 period are from Koch and others (2014). Euro prices are converted to dollars at the rate of $1.15 per €1, the exchange rate as of January 10, 2019.

16. 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. Also see Lewis (2018). Rules for adding allowances to or withdrawing from the EU's Market Stability Reserve were established in 2015 to go into operation in 2019. As of May 2018, the EU 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 Market Stability Reserve.

17. A similar problem bedevils the Regional Greenhouse Gas Initiative, a cap-and-trade system for electricity in the U.S. Northeast (Metcalf 2019).

the cap-and-trade law passed by the U.S. House of Representatives in 2009 that ultimately failed in the Senate. A free allowance 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 10-year period.[18]

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 CO_2 cap-and-trade program and gave allowances to the firms that were subject to the cap.[19] Whether this is fair is a matter of debate. But the very complexity of the cap-and-trade approach means that the public did not really understand the massive transfer taking place in the EU's ETS or that would have taken place if the U.S. cap-and-trade legislation had gone into effect.

II.B. Regulation

Although 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 U.S. federal level are the corporate average fuel economy (CAFE) standards and the regulation of CO_2 emissions in the power sector under the Clean Air Act. Recall that transportation and electricity generation each accounted for about 36 percent of energy-related CO_2 emissions in 2016. These two regulatory targets thus account for nearly three-quarters of these emissions.

After the U.S. Supreme Court ruled in 2007 that GHGs were air pollutants that could be regulated under the Clean Air Act, the EPA in 2009 issued an endangerment finding 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

18. Congressional Budget Office Cost Estimate of HR 2454, June 5, 2009 (https://www.cbo.gov/publication/41189).

19. Smale and others (2006) examine five energy-intensive sectors in the United Kingdom and conclude that profits in most of the sectors rise following the imposition of a cap-and-trade system with free allowance allocation.

Soren Anderson and James Sallee (2016). Taxes on emissions—for transportation, this can be translated into a tax on gasoline use—create incentives for consumers to purchase more fuel-efficient vehicles, drive fewer miles in the aggregate, and scrap fuel-inefficient vehicles sooner. A fuel economy standard mandating that an automaker'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 thus 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 Howard 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. Valerie Karplus and others (2013), for example, find that fuel economy standards are 6 to 14 times more expensive than a fuel tax to achieve the same emission reductions.[20] Mark Jacobsen (2013) finds CAFE is a little over three times the cost of a gasoline tax per ton of CO_2 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 2022–25 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.[21]

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.[22] 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 the 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,

20. 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 that results from the way the taxes are designed.

21. *Federal Register* 74, no. 59: 14196–556. The model year 2022–25 standards are described by NHTSA (2011).

22. The final plan was published in *Federal Register* 80, no. 205 (October 23, 2015): 64661–65120.

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 electricity-generating sector. All this is moot, however, because then–EPA administrator Scott Pruitt issued a proposed rule to repeal the Clean Power Plan in October 2017 (Eilperin 2017). Because the endangerment finding is still in place, the 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 regulations and the Clean Power Plan illustrate the political vulnerability that results from using regulation to advance mitigation goals. In August 2018, the Trump administration announced a reworking of the model year 2022–25 standards as the Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule that would freeze fuel economy standards at model year 2020 levels through model year 2026 (NHTSA 2018). 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 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.

II.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; so though the aggregate cost of the subsidy might be large, the cost to any individual may be too small to notice.

Renewable Portfolio Standards (RPSs) are common policies at the state level. RPS programs are a blend of regulation and subsidy and are currently in place in 29 states (North Carolina Clean Energy Technology Center 2018). 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 that it has satisfied its 15 percent RPS obligation. Companies demonstrate compliance by submitting renewable energy credits (RECs) to the state each year. RECs are like vouchers that the state gives to renewable electricity producers for every megawatt-hour (1,000 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 made 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 2 to 10 cents per kilowatt-hour, depending on the time of day the power is sold. The owner could also sell a REC to a utility that needs it to comply with the RPS rule. This might bring another 25 to 28 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.

Although the REC costs get passed on to ratepayers, the cost increase is blunted to some extent by the fact that wind and solar power have very low (essentially zero) operating costs. As a result, electricity prices do not 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 though a tax increase may be unpopular, it does raise revenue that could be returned to taxpayers 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 10 percent was over six times higher with an RPS program than with a carbon tax applied to fuels used to generate electricity.[23]

Rather than have the ratepayer pay for the subsidy, as in RPS programs, taxpayers could 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.[24] Historically, the biggest tax breaks have been tax credits for projects that generate electricity from solar, wind, geothermal, or other

23. 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 because 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.

24. 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 effects on domestic oil and gas production but are costly to the U.S. Treasury.

renewable sources. Currently, solar electricity and solar hot water projects are eligible for a 30 percent investment tax credit.[25] This credit is available for residential rooftop solar as well as utility-scale solar projects (for example, 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 10 years of operation. This 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 much 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. This is 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.[26]

Lowering consumer prices encourages more energy use. It also means that consumers buy fewer energy-efficient appliances and that factory owners invest less in energy-efficient equipment. Subsidies are also expensive. Production and investment tax credits reduce U.S. federal tax collections by about $3 billion a year (Metcalf 2018).

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

25. 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 by Carlson and Metcalf (2008).

26. The problem is not unique to Texas. Wald (2012) reports that the Chicago area experienced negative pricing 3 percent of the time in 2010.

The problem is that we cannot 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 do not really know whether half the sales would have occurred without the subsidy or if 80 percent of the sales would have occurred without the subsidy. 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.[27]

Besides being wasteful, energy subsidies disproportionately accrue to high-income households. A 2016 analysis of tax returns shows that 10 percent of energy tax credits go to the bottom 60 percent of the income distribution, while nearly two-thirds go to households in the top 20 percent.[28]

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 Volt bought 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 Volt raises the overall fuel economy of the fleet, and General

27. This may be too conservative. Consider energy-efficient windows. Let us say that a homeowner spends $2,000 to replace 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 that demand rises by 1 percent for each 1 percent reduction in price, this credit would induce just over 10 percent in new sales. In other words, 9 sales out of 10 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 70 percent of consumers claiming rebates for an energy-efficient appliance would have bought them anyway, and another 15 to 20 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).

28. This study was done by Borenstein and Davis (2016). Some tax credits are more regressive than others. The researchers document that 90 percent of the credits for electric vehicles go to households in the top 20 percent of the income distribution.

Motors is subject to a nationwide mandate on the overall fuel economy of the vehicles it sells.[29]

II.D. Information and Voluntary Programs

Energy experts and policymakers have increasingly focused on the potential for carefully packaged information to reduce energy consumption. Although information is valuable, it is not a viable climate policy. Hunt Allcott and Todd Rogers (2014), for example, show that these programs yield about a 2 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 an offset payment. Moreover, trading in offsets is minuscule relative to the emissions reduction need.[30]

III. Carbon Taxes around the World

Carbon taxes have been used by countries and subnational governments for more than 25 years. As of early 2019, 27 national or subnational carbon taxes were currently in effect or in the process of implementation.[31] There have been two waves of carbon tax enactments, First, a Scandinavian wave starting in the early 1990s saw carbon taxes legislated in Denmark, Finland, Norway, and Sweden, among other countries. By 2000, 7 countries had a carbon tax. A second wave in the mid-2000s saw carbon taxes put in place in Switzerland, Iceland, Ireland, Japan, Mexico, and Portugal. In addition, the Canadian provinces British Columbia and Alberta have

29. It is actually better than that for General Motors. For GHG emissions fleet limits, the 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, does not 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 45 miles per gallon gets treated as if it gets 45/0.15 = 300 miles per gallon. For more information, see Center for Climate and Energy Solutions (n.d.).

30. I discuss this in greater detail in Metcalf (2019).

31. Existing and planned carbon tax regimes are summarized by the World Bank Group (2018).

enacted carbon taxes. In 2019, Argentina implemented a carbon tax, and Singapore and South Africa are scheduled to implement carbon taxes in 2019. 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 $1 per ton of CO_2 to as much as $140 per ton for Sweden. A total of 12 countries have carbon tax rates of at least $25 per ton, and 6 have rates of at least $50 per ton.[32]

Given the range in carbon tax rates around the world, how should the United States set the tax rate if it implements a carbon tax? Pigouvian theory suggests the tax on carbon pollution should be set equal to the marginal damage from one more ton of CO_2 emissions.

In a world with preexisting market distortions, economists have argued that the optimal tax on pollution (of any type) will typically be less than the marginal damage.[33] Specifically, the optimal tax equals the marginal damage of pollution divided by the marginal cost of public funds. The larger are the tax distortions, the larger is the marginal cost of public funds and the smaller is the optimal tax relative to marginal damage.[34]

Whether one uses a first- or second-best Pigouvian approach, policymakers need an estimate of the marginal damage from CO_2 emissions. They could base their estimate on analyses of the social cost of carbon done by the EPA and other federal agencies during the Obama administration. This is a measure of damage designed for use in regulatory cost-benefit analyses as opposed to the Pigouvian prescription to measure the social marginal damage of emissions at the optimal level of emissions. The errors in measuring social marginal damage at current emission levels rather than optimal levels are likely to be swamped by errors in estimation from our

32. Rates are as of April 1, 2018, as reported by the World Bank Group (2018).

33. The first papers to make this point were those by Bovenberg and de Mooij (1994) and Parry (1995).

34. See Bovenberg and Goulder (2002) for a review of the literature on second-best environmental taxation and, in particular, section I. As a central case, Bovenberg and Goulder (1996) estimate the marginal cost of public funds to equal 1.25, which suggests that the optimal tax on pollution should be 20 percent lower than social marginal damage. The first-best rule that sets the tax on pollution equal to social marginal damage can be recovered if households have identical tastes, leisure is weakly separable from pollution and private goods, and a nonlinear 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 Pirttilä and Tuomala (1997). As Bovenberg and Goulder (2002) point out, these conditions—especially the last—are unlikely to be met.

imperfect state of knowledge about the full range of damage and risks of catastrophic events—events with a high impact but low probability.[35] With this caveat in mind, a tax rate based on the social cost of carbon would be roughly $50 a metric ton of CO_2 in 2020.[36]

A second approach would be to set a tax rate to hit a revenue target over a 10-year budget window. The U.S. Department of the 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 10-year budget window (Horowitz and others 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 80 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. Economic and engineering analyses suggest that an 80 percent reduction by 2050 is possible but would require significant advances in technology along with strong political will.[37] Whether policymakers settle on an 80 percent reduction by 2050 or some other target, a carbon tax will likely be designed with some emissions reduction target in mind.

Let us assume this is the case. How do you ensure you hit the target given our use of a carbon tax? One way to do this is to enact a carbon tax with a "policy thermostat" that adjusts the tax rate in a known and

35. 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 seen as an insurance policy rather than as a Pigouvian price adjustment.

36. The $50 figure is based on the estimate by the U.S. Interagency Working Group on the Social Cost of Carbon (2016) for 2020 equal to $42 in 2007 dollars. I have converted the estimate to 2020 dollars using the Consumer Price Index 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 cause estimates of the optimal tax on emissions to fall short of social marginal damage, as discussed in the notes above. Pindyck (2017) is a prominent critic of using the Interagency Working Group's methodology to set the tax rate on carbon dioxide.

37. Heal (2017) argues that an 80 percent reduction by 2050 could be achieved at "reasonable cost"; he estimates a cost of about 1 percent of GDP. His scenario, however, requires strong financial incentives and political support along with significant reductions in the cost of renewables and battery storage. Williams and others (2014) come to a similar conclusion.

predictable way between now and some future date to increase the likelihood of hitting emission reduction targets 15 to 30 years out.[38]

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: a tax rate that is adjusted statutorily if emission reduction goals are not met. Sweden's carbon tax has the highest rate in the world, and it has gradually moved to eliminate all discounted rates for energy-intensive sectors subject to the tax.

III.A. British Columbia

As part of a broader package of tax reforms, the Canadian province of British Columbia (BC) enacted a broad-based carbon tax in 2008 starting at \$10 (Canadian; hereafter, C\$) per metric ton of CO_2 and increasing by C\$5 per year to its current C\$35 (as of 2018), equivalent to US\$27.[39] The tax is scheduled to increase by C\$5 per year until it reaches C\$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.

The tax collects over C\$1 billion annually—over 5 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 (British Columbia Ministry of Finance 2019). Worried that the new carbon tax would disproportionately affect low-income households, policymakers included several elements in the tax reform to offset adverse effects on them. One element was a low-income climate action tax credit of C\$154.50 per adult plus C\$45.50 per child (as of July 2019), which reduces taxes by C\$400 for a low-income family of four. In addition, when first implemented, tax rates in the lowest two tax brackets were reduced by 5 percentage points (Harrison 2013). Also, in the first year of the carbon tax, there was a one-time "climate action dividend" of C\$100 for every resident of BC.

38. I propose such a rate adjustment mechanism, called the Emissions Assurance Mechanism, in Metcalf (forthcoming).

39. All currency conversions to U.S. dollars (C\$1 = US\$0.78) use exchange rates as of late May 2018. Information about the tax rate is taken from https://www2.gov.bc.ca/gov/content/environment/climate-change/planning-and-action/carbon-tax.

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 C$10 to C$20, there was more carbon tax revenue to rebate, much of which was channeled to businesses in the form of new business tax credits.

BC's carefully constructed policy package to return tax revenue to its residents and businesses balanced concerns about distributional effects and economic growth. Targeting tax cuts to low-income households ensured that the burden of the tax would not fall disproportionately on these households. And the focus on small business emphasized the importance of supporting economic growth.

Canada has moved to a national price on carbon pollution. As of April 2019, every province was required to have a plan in place to price carbon emissions. Failing that, the national government will impose a tax at C$20 per metric ton (Wingrove 2019). Because BC has a carbon tax in place, the federal tax will not be operative in the province.

III.B. Switzerland

Switzerland introduced a carbon tax in 2008 on fuels used for stationary sources (that is, 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.[40] One-third of the revenue collected—up to 450 million Swiss francs (hereafter CHF)—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 the 2011 revision of the law: if emissions in 2012 exceeded 79 percent of

40. 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.

Table 1. The Swiss Carbon Tax[a]

Tax rate (CHF)	*Enactment date*	*Trigger for a tax rate increase*
12	2008	Not applicable
36	2010	Not applicable
60	2014	Tax rises to CHF 60 if emissions exceed 79 percent of 1990 emissions in 2012
84	2016	Tax rises to CHF 72 if emissions exceed 76 percent of 1990 emissions in 2014 Tax rises to CHF 84 if emissions exceed 78 percent of 1990 emissions in 2014
96	2018	Tax rises to CHF 96 if emissions exceed 73 percent of 1990 emissions in 2016 Tax rises to CHF 120 if emissions exceed 78 percent of 1990 emissions in 2016

Sources: International Energy Agency (2018a); Swiss Carbon Tax Ordinance.
a. CHF = Swiss francs. All tax rate changes go into effect at the beginning of the year.

1990 emissions, the tax rate would increase to CHF 60 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 CHF 96 (US$99).[41] The Swiss tax provides an example of a hybrid carbon tax where rates adjust in response to deviations from desired targets (hence, it is a hybrid of a tax and cap-and-trade system). I discuss a possible hybrid carbon tax design feature in section V below.

III.C. Sweden

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 a rate of SEK 250 (US$27) to its current rate of SEK 1180 (US$127).[42]

Sectors covered under the EU's ETS are exempt from the tax. Other industrial sectors were initially subject to a lower rate (one-quarter of the standard rate). The rate differential was gradually narrowed, until it was eliminated in 2018.[43] Although the general rate today is 4.72 times its

41. Conseil Federal Suisse, "Ordonnance sur la Reduction des Emissions de CO_2," enacted December 23, 2011 (RS 641.71). Tax rates were reported by the International Energy Agency (2018a, 278). The currency exchange rate is as of mid-September 2018.

42. Exchange rate of SEK 1 = US$0.11, as of February 13, 2019.

43. This information is from https://www.government.se/government-policy/taxes-and-tariffs/swedens-carbon-tax/.

initial rate, carbon tax collections in 2017 were 3.4 times collections in 1994 (the first year for which the Swedish tax authority published data).[44] 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.[45] Sweden's growth rate has exceeded that of the United States 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. The Swedish economist Thomas Sterner notes that though fossil fuels used for home heating are part of the tax base, little in the way of a carbon tax is collected on home heating fuels due to a shift away from fossil fuels for this purpose, a shift that Sterner argues is due largely to the carbon tax.[46]

Runar Brännlund, Tommy Lundgren, and Per-Olov 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 vehicle sectors had the highest improvements in emissions intensity, while paper and pulp had the lowest improvements in emissions intensity (albeit a positive improvement).

IV. Economic Outcomes of Carbon Taxes

The literature on the economic effects of carbon taxes is somewhat thin, in part because few broad-based carbon taxes have been in place for a long enough time to assess. Here, I present some regression estimates for emissions and GDP for the Canadian province of British Columbia. Its tax, which has been in place since 2008, is a broad-based assessment on fossil

44. Carbon tax data were downloaded from https://skatteverket.se/omoss/varverksamhet/statistikochhistorik/punktskatter/energiskatterochandramiljorelateradeskatter.4.3152d9ac158968eb8fd24b2.html.

45. The Swedish GDP data are from the World Bank, and the emissions data are from Statistics Sweden (http://www.statistikdatabasen.scb.se).

46. Personal communication, February 12, 2019.

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 the results of recent modeling economic efforts. The Stanford Energy Modeling Forum (EMF) recently completed a major study (EMF 32) of the economic outcomes of a U.S. carbon tax (Fawcett and others 2018). James McFarland and others (2018) describe the study and the 11 economic models that it analyzed. 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 do not. Conversely, model results are driven by model assumptions, which may not always be perfectly transparent.

IV.A. Emissions

Alexander Barron and others (2018) summarize results from Stanford University's EMF 32 study of a U.S. carbon tax. The 11 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.[47] A tax of $50 per ton yields a decrease of 11 to 25 percent in emissions in 2020. Over a 10-year period, the models analyzed 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 carbon tax of $50 per ton rising at 5 percent a year, the 10-year emissions decline ranges from 22 to 38 percent, with an average of 30 percent.

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 effects over the decade), consider the following calculation. The aggregate consumer price of fossil fuels in 2020, based on the reference scenario of the U.S. Energy Information Administration's (EIA's) (2018) *Annual Energy Outlook*, is $13.87 per million British thermal units (BTUs).[48] Based on the average CO_2 content of each fossil fuel, a carbon tax of $25 ($50) translates

47. Barron and others (2018, 9) report emission reductions of 16 to 28 percent below 2005 levels. Reference-level emissions are about 10 percent below 2005 emissions, according to McFarland and others (2018, figure 2).

48. Prices are consumer prices for nonmetallurgical coal, gasoline, and natural gas (table 3). Consumption shares on a BTU basis are used to average the prices (table 1).

into about \$1.86 (\$3.73) per million BTUs of fossil fuel consumption. A carbon tax of \$25 per ton would increase the consumer price of fossil fuel energy by about 13 percent if fully passed forward to consumers. This suggests an emissions price elasticity of $-.12/.13 \cong -1.0$, using the midpoint of the immediate emission reduction estimates. The 10-year elasticity (based on the average of the study estimates) is about –1.5. Using the carbon tax of \$50 a ton, the immediate emissions price elasticity is about –0.67, and the 10-year elasticity is about –1.11.[49]

Turning to econometric analyses of existing taxes, Boqiang Lin and Xuehui 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, the Netherlands, Norway, Denmark, and Sweden—with 13 European countries selected as controls. Regressions are run over the 1981–2008 time frame. In 4 of the 5 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. These researchers argue that the larger effect for Finland reflects the smaller number of exemptions from the tax than in other countries.

Ralf Martin, Laurie de Preux, and Ulrich Wagner (2014) consider the impact of the United Kingdom's Climate Change Levy (CCL) on various manufacturing firms' 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), as reported by Martin, de Preux,

49. The \$25 carbon tax is modeled to grow at 1 percent real, so it equals \$28 at the end of the decade. The \$50 rate is modeled to grow at a real 5 percent and equals \$81 at the end of the decade. If I compute the 10-year elasticity for the \$50 rate using the average of the initial and final rates, I get a price elasticity estimate of about –0.86. 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 fell by 2.3 percent relative to a counterfactual of a zero-carbon tax between 1990 and 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 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.

and Wagner (2014, table 1). 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 cannot rule out the possibility that the CCL has led to fuel substitution away from electricity and toward coal.[50]

Nicholas Rivers and Brandon Schaufele (2015) consider the impact of BC'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 (based on the tax rate). Although an increase of 1 cent per liter in the price of gasoline depresses gasoline consumption in BC by 0.41 percent, an increase of 1 cent per liter in the carbon tax reduces demand by 1.7 percent—a fourfold increase. The authors attribute the difference to the high salience of the carbon tax.

Looking at province-level emissions, Stewart Elgie and Jessica McClay (2013; updated by 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.

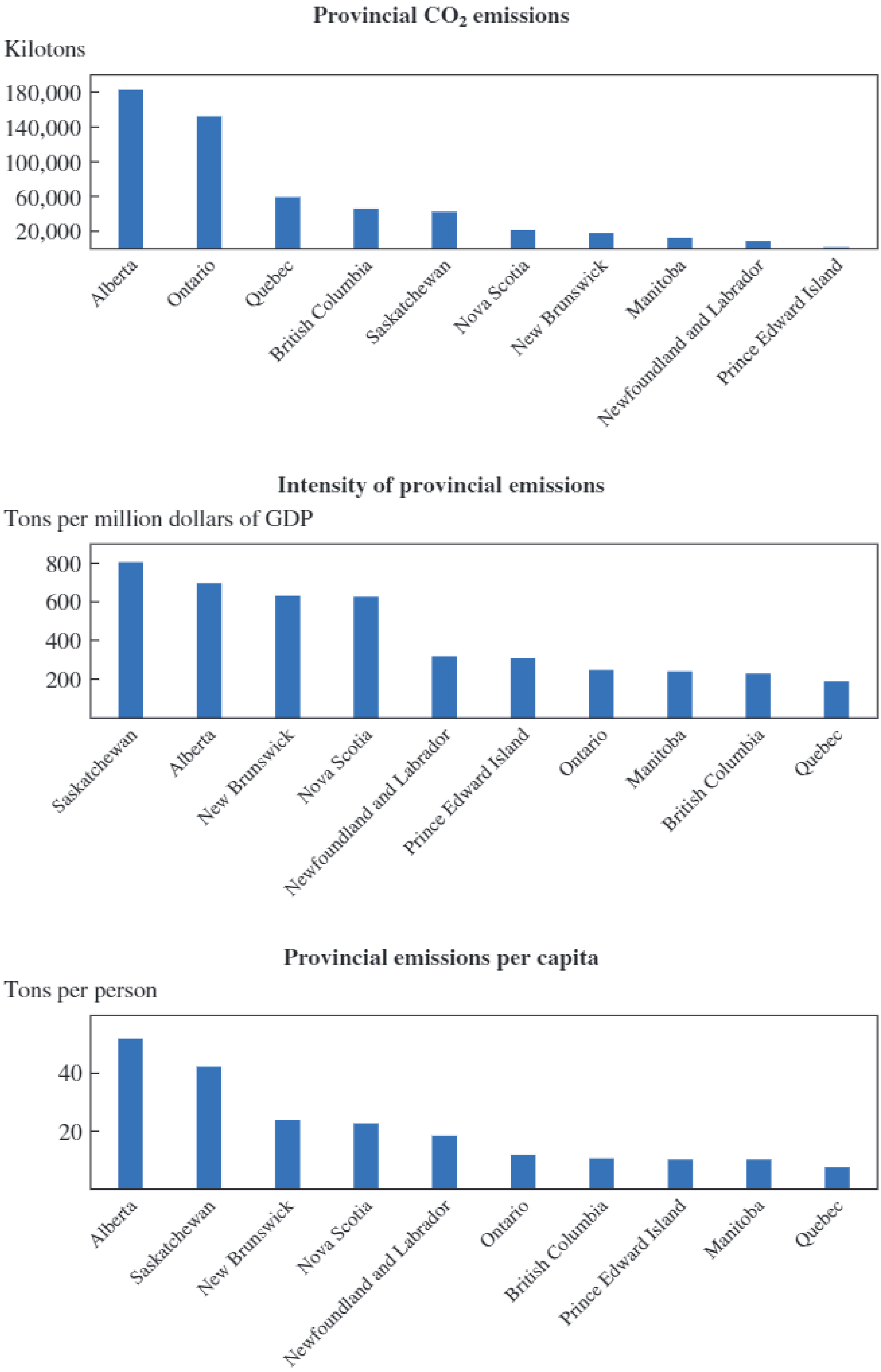
I next present some regressions on annual province-level CO_2 emissions over the period 1990–2016. I present difference-in-difference regressions for a BC carbon tax treatment relative to provinces and territories that have not implemented some form of carbon pricing as well as regressions with carbon prices for the carbon pricing programs in BC, Quebec, and Alberta.

Alberta imposed a price on emissions in July 2007 called the Specified Gas Emitters Regulation. 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 though BC was a moderately large source of CO_2 emissions in Canada in 2007 (the top panel of figure 2), it is a small emitter on a per capita basis (the middle panel of figure 2) or per dollar of GDP (the bottom panel of figure 2). It is perhaps not surprising that three of the four provinces that have moved forward with carbon-pricing programs (BC in 2008, Quebec in 2013, and Ontario in 2017) have very low emissions per capita or low emissions intensity. Alberta, conversely, is a top emitter on nearly all three metrics.

50. 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.

Figure 2. Provincial Measures of CO_2 Emissions in Canada, 2007



Source: Appendix, table A2.

Table 2 presents CO_2 emission regressions for the Canadian provinces and territories over the period 1990–2016.[51] 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 am 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 because it has an ambitious feed-in tariff for renewable energy (enacted in 2009) that is unique among Canadian provinces.[52] Dropping these three provinces increases the impact of the BC carbon tax. Now emissions fall in the posttax 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 1 percent level.

Table 3 provides results when the carbon prices for Alberta, Quebec, and BC are included.[53] 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 (BC's rate in 2012) reduces emissions by 7.8 percent, a result consistent with the results in table 2.

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

IV.B. GDP

Table 4 reports similar regressions with ln(GDP) as the dependent variable. Unlike the emission regressions, I also consider variables that

51. The data sources for the regressions in tables 2 through 5 are given in the appendix at the end of this paper, in table A2.

52. Ontario's feed-in tariff is described at https://www.ontario.ca/document/renewable-energy-development-ontario-guide-municipalities/40-feed-tariff-program.

53. Quebec's rate is C\$3.50 starting in 2007. A cap-and-trade system went into effect in 2013, and I include average allowance auction prices for each year. Alberta enacted the Specified Gas Emitters Regulation in 2007 at a rate of \$15 per ton.

Table 2. Carbon Dioxide Emission Regressions: British Columbia (BC), Difference-in-Difference[a]

	(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	Excludes AL, ON, QC	Excludes AL, ON, QC	Excludes AL, ON, QC	Excludes AL, ON, QC
Years	1990–2016	1990–2016	1995–2016	1990–2016	1995–2016
Observations	360	279	234	279	234
R^2	0.998	0.996	0.996	0.939	0.9981

Source: Appendix, table A2.

a. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. AL = Alberta; ON = Ontario; QC = Quebec. All regressions include province and year fixed effects. The dependent variable is ln(CO_2 emissions). GDP and population are in logs. Regressions 4 and 5 have the ln of CO_2 per dollar of GDP as the dependent variable. Standard errors are in parentheses and are clustered at the province level.

Table 3. Carbon Dioxide Emission Regressions—Tax Rates[a]

	(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^2	0.998	0.997	0.998	0.958	0.957

Source: Appendix, table A2.

a. $***p < 0.01$, $**p < 0.05$, $*p < 0.1$. ON = Ontario. All regressions include province and year fixed effects. The dependent variable is ln(CO_2 emissions). GDP and population are in logs. Regressions 4 and 5 have the ln of CO_2 per dollar of GDP as the dependent variable. Standard errors are in parentheses and are clustered at the province level.

Table 4. GDP Regressions: BC Difference-in-Difference[a]

	(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 share		0.2974	0.2869	0.1756
		(0.3736)	(0.6240)	(0.6226)
Professional share		–1.4859	–2.5594	–2.7270
		(1.0505)	(1.4941)	(1.6554)
Public sector share		–0.7057	–0.0253	–1.1626
		(0.8856)	(0.9117)	(0.8190)
Natural resources share		0.9055	0.1708	0.0537
		(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 AL, QC, ON	Provinces less AL, QC, ON
Years	1990–2016	1990–2016	1990–2016	1995–2016
Observations	360	270	189	154
R^2	0.999	0.999	0.999	0.999

Source: Appendix, table A2.

a. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. AL = Alberta; ON = Ontario; QC = Quebec. All regressions include province fixed effects. The dependent variable is ln(GDP). Canadian GDP and population are in logs. Standard errors are in parentheses and are clustered at the province level.

measure the composition of economic activity in provinces and territories. Specifically, I include the share of workers in the employment categories of manufacturing, professional services, the public sector, and natural resources.[54] Regressions include province fixed effects. Rather than year fixed effects, I include Canadian GDP (in logs) to control for business cycle effects at the national level. Column 1 of the table 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

54. Natural resources includes forestry, fishing, mining, quarrying, oil, and gas. I do not include these share variables in the emission regressions, because I would expect the carbon tax to reduce emissions, in part, by shifting the composition of economic activity.

Table 5. GDP Regressions—Tax Rates[a]

	(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 share		0.3312	0.4136	0.3205
		(0.3599)	(0.4239)	(0.3648)
Professional share		–1.6006	–1.7846	–2.3823*
		(1.0612)	(1.1229)	(1.2465)
Public sector share		–0.6915	–0.6474	–1.1353
		(0.8879)	(0.9814)	(0.6643)
Natural resources share		0.7830	0.6903	0.4506
		(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^2	0.999	0.999	0.999	0.999

Source: Appendix, table A2.

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

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 9.23 percent and is 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.[55] These GDP results are consistent with simpler regressions run in my 2016 paper, although

55. These regressions suggest that the BC carbon tax led to higher GDP. Regressions not reported here suggest that the tax may have raised the growth rate of BC's GDP by as much as 1 percent.

those results were an order of magnitude smaller. 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 have a positive impact on growth. Second, some of the revenue was specifically directed to lower-income households. To the extent that these households have higher marginal propensities to consume out of income, this could, as well, support economic growth in the short run.

As additional evidence on the GDP effects of a carbon tax, I provide analysis using variation in carbon tax implementation in European countries; see table 6 for the regression results.[56] I focus on countries that are part of the ETS, a cap-and-trade system covering the power sector and certain other energy-intensive sectors (see above).[57] These countries have a uniform treatment of emissions under the cap-and-trade system. Fifteen of these countries have enacted carbon taxes on top of the ETS, covering sectors or firms within sectors not covered by the ETS. Although one should be cautious in interpreting results of regressions of GDP on an indicator for the presence of a carbon tax as causal, the regressions can shed light on whether GDP is adversely affected by the presence of a carbon tax. Data on 31 countries are analyzed over the period 1985–2017. The first carbon tax in the sample went into effect in 1991.

The first regression shown in table 6 regresses the log of real GDP against an indicator variable for the presence of a carbon tax. The regression includes Organization for Economic Cooperation and Development (OECD)–wide ln(GDP) and country fixed effects. The GDP effect is positive, with a 3.89 percent increase in EU country GDP, but is not statistically significant. The second regression adds a variable interacting the indicator with a variable measuring the share of the country's emissions covered by the carbon tax at the beginning of 2019.[58] In contrast to the BC carbon tax, which applies to all emissions in the province, carbon taxes vary across Europe in scope of coverage. To capture differential coverage, I include

56. Data sources for these regressions are given in the appendix, in table A3.

57. I also include Switzerland, which has its own cap-and-trade system that is closely aligned with the ETS. The two systems will be formally linked starting in 2020.

58. The World Bank's Carbon Pricing Dashboard maintains information on current carbon tax rates and coverage. Its data go back to 2016. Data on earlier years are not available.

Table 6. GDP Regressions for the European Union[a]

	(1)	(2)	(3)	(4)	(5)	(6)
Carbon tax indicator	0.0389	0.0814	0.0335	0.0309	0.166	0.106
	(0.0545)	(0.137)	(0.131)	(0.0693)	(0.177)	(0.171)
Interaction with emissions share		–0.144	0.0260		–0.447	–0.260
		(0.411)	(0.388)		(0.483)	(0.462)
OECD ln(GDP)	1.178***	1.179***				
	(0.0913)	(0.0907)				
OECD ln(GDP per capita)				1.416***	1.421***	
				(0.119)	(0.119)	
Constant	–8.363***	–8.387***	12.67***	–4.493***	–4.554***	10.65***
	(1.596)	(1.585)	(0.0401)	(1.244)	(1.246)	(0.0435)
Tax effect at median emissions share		0.0341	0.0420		0.0181	0.0203
		(0.0539)	(0.0514)		(0.0607)	(0.0657)
Observations	918	918	918	912	912	912
R^2	0.830	0.830	0.848	0.746	0.751	0.779
Year fixed effects	No	No	Yes	No	No	Yes

Source: Appendix, table A3.

a. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. OECD = Organization for Economic Cooperation and Development. All regressions include country fixed effects. Dependent variable is ln(GDP) in regressions 1 through 3 and ln(GDP per capita) in regressions 4 through 6. Regressions are run for 1985–2017. Standard errors are in parentheses and are clustered at the country level.

this interaction variable. The coefficient on the carbon tax indicator variable is positive, and the interaction coefficient negative. The interquartile range of GDP effects, given the distribution of the share variable conditional on having a carbon tax, runs from 2.4 percent (for the 75th percentile of the share of covered emissions) to 6.0 percent (for the 25th percentile). The impact for the median covered emissions share is 3.4 percent (reported in table 6). In no case is the impact statistically significant at any reasonable level. The third column adds year dummies with no appreciable impact on the effects.

The final three columns of table 6 run regressions on the log of per capita real GDP. The results are not materially different. The regressions, as a group, suggest that imposing a carbon tax has not adversely affected GDP in countries that have levied a carbon tax. If anything, there appears to have been a modest positive impact—if we take the coefficient estimates at face value. I have not explored the mechanism underlying this positive impact (if, indeed, it holds up). Many early carbon tax reforms used carbon tax revenues to lower income tax rates as part of a green tax reform movement in the early 1990s, especially in those Nordic countries with very high income tax rates (Brännlund and Gren 1999). Lowering especially high income tax rates through a carbon tax reform could stimulate economic activity. More ex post analysis of existing carbon tax systems would be extremely valuable, both for assessing the macroeconomic effects of a carbon tax and for calibrating economic models that are typically used to assess climate policy. Such analyses would also be valuable for teasing out the mechanisms driving economic growth—if they hold up in subsequent research.

IV.C. Employment

As part of their analysis of the United Kingdom's 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 U.K. manufacturing.

Akio Yamazaki (2017) constructs employment data on 68 industries across Canadian provinces and territories for the years 2001–13 to investigate the BC 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 (a redistribution effect). Finally, employment could rise (or fall) if labor is a substitute (or a complement) for energy (factor substitution effect). His study focuses on the first two channels of employment effects. He finds that the output effect dampens employment while the redistribution effect enhances employment. In the aggregate, he finds a modest positive and statistically significant impact on employment, on the order of 0.75 percent annually. Jobs are shifting, however, from carbon- and trade-sensitive sectors to sectors that are less carbon and trade sensitive. Chemical manufacturing, for example, has the largest decline in employment, while health care has the largest increase.

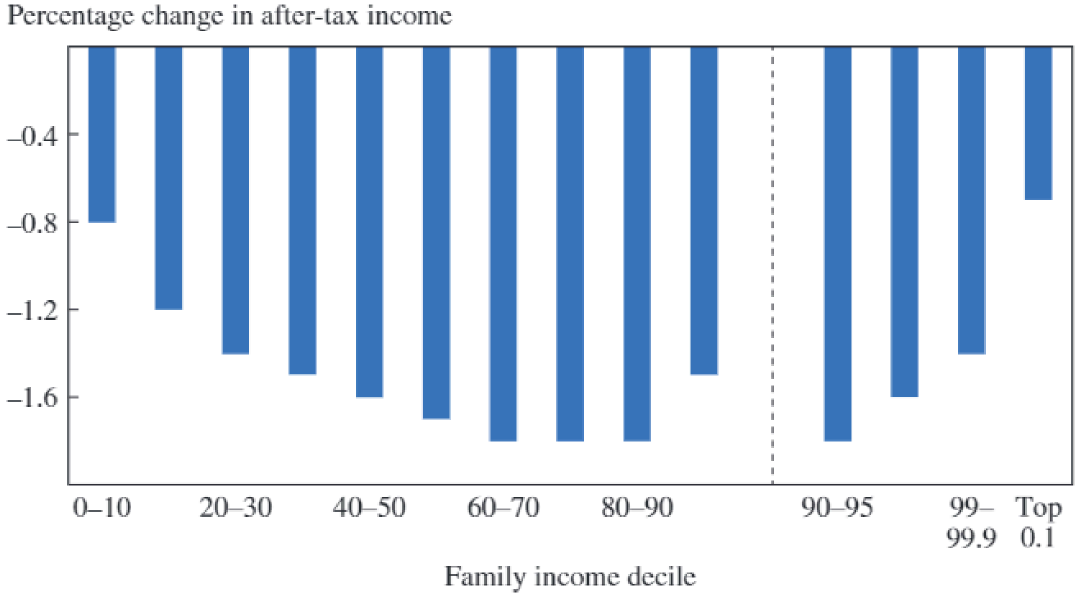
IV.D. Distributional Outcomes

Numerous distributional analyses have been done of a carbon tax for the United States. Distributional effects arise from differential consumption of carbon-intensive goods whose prices have gone up relative to the general price index versus carbon-light goods whose prices have fallen relative to the general price index. This is the *use 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 that are disproportionately important for lower-income households.[59] Lawrence Goulder and others (forthcoming) show in a computable general equilibrium analysis that the source side effects fully offset the use side effects, so that the carbon tax, ignoring the use of revenue, is distributionally neutral to slightly progressive.

Metcalf (1999), among others, has argued that one should focus on the distributional effects of 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 and others 2017) illustrate this. Figure 3 shows the carbon tax, ignoring the use of revenue. The Treasury's analysis finds it is progressive up through the

59. Rausch, Metcalf, and Reilly (2011) and Goulder and others (forthcoming), among others, have argued that use-side, regressive effects are offset by progressive, source-side effects. Transfers are also important in explaining the source-side, progressive effects. Fullerton, Heutel, and Metcalf (2011) also stress the importance of transfers.

Figure 3. The Carbon Tax Burden, Ignoring the Use of Revenue



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

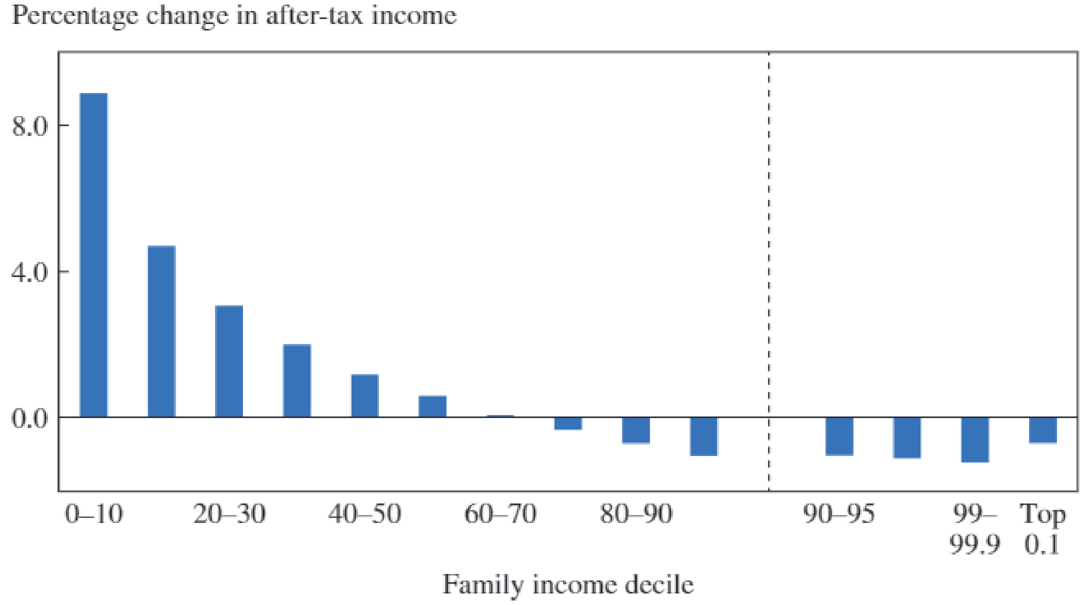
7th and 8th deciles. It then turns regressive in the top deciles. With the equal per capita rebate, shown in figure 4, the tax reform is sharply progressive. In fact, households up through the 70th percentile are better off, in the sense of receiving more in the rebate than the effects on disposable income through source and use side effects. Note, however, that these graphs are showing average distributional effects at each decile. Various researchers have noted that there can be considerable heterogeneity within a decile (Rausch, Metcalf, and Reilly 2011; Cronin, Fullerton, and Sexton 2017).

V. Policy Thoughts

In this paper, I do not address the details of how one would implement a carbon tax. This topic has been covered elsewhere—by Metcalf and David Weisbach (2009), Metcalf (2017), and Horowitz and others (2017). In brief, an excise tax on coal, natural gas, and petroleum products can piggyback on existing fuel excise taxes (for petroleum and coal). Additional process emissions can easily be taxed, such that roughly 90 percent of domestic GHG emissions (excluding forestry and land-use changes) can be included in the tax base.[60]

60. See Metcalf and Weisbach (2009) for further discussion.

Figure 4. The Carbon Tax with Equal Rebates per Person



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

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

Second, a federal carbon tax will need 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 CO_2 in imported goods and services is more difficult. Wayne 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 nontrivial task, and Metcalf and Weisbach (2009) propose setting the tax on the basis of the emissions content of 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 persuade millions of economic agents to adjust their behavior in large and small ways to reduce emissions. Although 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 GHG pollutants not amenable to taxation, and institutional barriers suggest the need for a range of policies.

As discussed in the introduction, the United States' transition to a zero-carbon economy will require new inventions and production processes. Research and development will be key to the successful diffusion of these technologies. Information and new knowledge are pure public goods that are underprovided in a market economy. A carbon tax should be complemented with 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 (for example, wind from the Midwest and hydropower from Canada).[61] 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.[62]

Although 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 carbon tax reform. My policy framework for a national carbon tax includes (1) revenue neutrality, (2) a focus on fairness, (3) streamlined policy, and (4) significant emission reductions.

Revenue neutrality ensures that long-contentious partisan differences over the size of the federal budget should not be allowed to affect the

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

62. The National Academy of Sciences (2019) lays out a research agenda to address the various barriers and high costs of carbon capture and storage.

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 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 program. 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 would also increase the efficiency of the U.S. 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, Wyoming, and Pennsylvania together account for one-third of coal-mining jobs. No other state comes close to the number of coal miners in these 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 (2 percent), 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 postcoal economy.[63]

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

63. All employment data are for 2017. Coal-mining employment is taken from the EIA's *Annual Coal Report 2017*, and total employment is taken from the U.S. Census Bureau's Quarterly Workforce Indicators, which are available at https://qwiexplorer.ces.census.gov.

and production if we cannot 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 cannot raise the cost of the polluting fuel, then the next best thing is to lower the cost of the nonpolluting fuel. But if we enact a carbon tax, a reasonable bargain is to eliminate those tax preferences, for a savings of roughly $6 billion a year.[64]

Next, consider the Clean Air Act and the endangerment finding that CO_2 should be regulated under the act. Although 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 the EPA's regulatory authority over GHG emissions but suspend any regulatory action for emissions covered by a carbon tax as long as demonstrable progress in reducing emissions is being made. This, of course, requires that we define "progress." Progress could be measured as a target reduction in emissions relative to a given base year (for example, 2005 emissions) at various milestone years between now and 2050. Failure to hit the targeted emission reductions would automatically trigger resumption of the EPA's regulatory process under the Clean Air Act. An independent commission or advisory group established under law could oversee progress toward the emission reductions. In addition, the carbon tax could be designed so the tax rate automatically adjusts over time to keep the United States on target to reach long-run emission reduction goals.[65]

This is not to argue that *all* GHG regulations should be put on hold. It is not realistic to subject all GHG emissions to a carbon tax. Some emissions are simply too hard to measure. A good example is the methane emissions associated with fossil fuel extraction. Methane is a potent GHG with a short-run impact on the environment 30 times that of CO_2. When underground coal mining was the dominant source of coal in the

64. This is a 10-year average (over the period 2019–28) of the tax expenditure estimates for energy production and investment tax credits, as reported by OMB (2019).

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

United States, coalbed methane was a major source of GHG 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 drilling 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 that equipment be used to minimize methane leaks. This would be coupled with strong monitoring and enforcement. Similarly, agricultural and land use emissions are difficult to tax and thus are more suitable for regulation.

In summary, we need to avoid a "bait and switch" situation, whereby regulatory oversight over GHGs is traded for a carbon tax, only to find that 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, it is likely that we will need a robust carbon price. The 2014 Stanford EMF modeling exercise found that a 50 percent reduction in U.S. emissions by 2050 would require a carbon price between \$10 and \$60 per ton of CO_2 in 2020 (looking across the bulk of models and technology assumptions) and between \$100 and \$300 in 2050. Although the international climate negotiations have focused on a target of an 80 percent emissions reduction by 2050 from 2005 levels, most research suggests that this will be extremely expensive. The Stanford modeling study corroborates this. The participating modelers estimate that the 2050 price on CO_2 required to hit that target would be somewhere in the range from \$200 to more than \$500 a ton, depending on model assumptions.[66]

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 CO_2 emissions will help spur this development. Given the very high (and probably politically unacceptable) cost of an 80 percent emissions reduction, a more modest but still aggressive

66. The Stanford Energy Modeling Forum exercise (EMF 24) is described by Clarke and others (2014).

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 45 percent reduction in CO_2 emissions (relative to 2005 levels), for example, would be ambitious but within reach. A subsequent target could be set for 2050, with an emissions reduction perhaps somewhere in the range of 60 to 80 percent by 2050, with the precise target set as new information emerges over the first 15 years about the damage from both GHG emissions and clean energy technology costs.[67]

Any target set out in carbon tax legislation could be conditioned on OECD member countries also committing to this goal within a short time frame and the major non-OECD emitting countries committing to this 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.[68]

Once the goal is set, the carbon tax should contain a mechanism for adjustment to ensure that the target is met. One simple way to do that would be to enact a carbon tax with an initial tax rate (for example, $40 a ton of CO_2 emissions). The legislation would also include a clear and transparent rule for adjusting the tax rate over time to hit emission reduction benchmarks, as 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.[69]

The carbon tax should also be designed so that there is the political will to sustain high tax rates on emissions. The authors of the Climate Leadership Council's carbon tax and dividend plan argue that the dividend

67. Metcalf (forthcoming) discusses the use of sequential targets for a carbon tax and proposes a 45 percent reduction by 2035 that would be consistent with a 60 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.

68. Nordhaus argues that nonparticipating 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.

69. 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).

will help build political support for high tax rates because, as rates rise, so would dividends.[70] They may or may not be right; but they are 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.

VI. Conclusion

A carbon tax is a cost-effective policy tool to reduce the United States' GHG emissions. It would be easy to implement, easy to administer, and straightforward for firms' compliance. With 23 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 encouraging that bipartisan support for a carbon tax is growing. Although 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.

ACKNOWLEDGMENTS James Stock, Larry Goulder, and Adele Morris provided helpful comments on early drafts of this paper. Ozgur Bozcaga provided invaluable research assistance on this project.

70. Baker and others (2017, 3) write: "It is essential that the one-to-one relationship between carbon tax revenue and dividends be maintained as the plan's longevity, popularity, and transparency all hinge on this. Allocating carbon tax proceeds to other purposes would undermine popular support for a gradually rising carbon tax and the broader rationale for far-reaching regulatory reductions."

Appendix

Table A1. Carbon Taxes around the World[a]

Jurisdiction	*Type*	*Year of implementation*	*Price (dollars)*	*Share of jurisdiction's GHG emissions covered*	*Revenue, 2018 (millions of dollars)*
Finland	National	1990	76.87	36%	1,609
Poland	National	1990	0.09	4%	1
Norway	National	1991	64.29	62%	1,725
Sweden	National	1991	139.11	40%	2,821
Denmark	National	1992	28.82	40%	593
Slovenia	National	1996	21.45	24%	92
Estonia	National	2000	2.48	3%	3
Latvia	National	2004	5.58	15%	10
British Columbia	Subnational	2008	27.13	70%	1,107
Liechtenstein	National	2008	100.90	26%	4
Switzerland	National	2008	100.90	33%	1,232
Iceland	National	2010	35.71	29%	57
Ireland	National	2010	24.80	49%	552
Ukraine	National	2011	0.02	71%	4
Japan	National	2012	2.74	68%	2,487
United Kingdom	National	2013	25.46	23%	1,145
France	National	2014	55.30	35%	9,551
Mexico	National	2014	3.01	46%	480
Spain	National	2014	24.80	3%	217
Portugal	National	2015	8.49	29%	171
Alberta	Subnational	2017	23.25	42%	1,080
Chile	National	2017	5.00	39%	145
Colombia	National	2017	5.67	24%	270

Source: World Bank Group (2018).

a. GHG = greenhouse gas emissions. Argentina, Singapore, and South Africa are scheduled to enact carbon taxes in 2019. The carbon tax rate reported is the main rate as of January 2018 reported in dollars. Revenue is an estimate for 2018. The share of emissions covered by the tax is as of January 1, 2019.

Table A2. Canada Province Regressions Data Sources

Variable	*Description*	*Source*
CO_2	Energy-related carbon dioxide emissions	Environment and Climate Change 2018 National Inventory Report (NIR), IPCC-Table C province and territory emissions. Downloaded from http://data.ec.gc.ca/data/substances/monitor/canada-s-official-greenhouse-gas-inventory/C-Tables-IPCC-Sector-Provinces-Territories/?lang=en.
GDP	Gross domestic product	Statistics Canada Table 36-10-0222-01. Expenditure-based GDP in chained $2007. Downloaded from https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3610022201.
Pop	Population, as of July 1	Statistics Canada Table 17-10-0005-01. Downloaded from https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1710000501.
Export Price	Price index for exports to other countries	Statistics Canada Table 36-10-0223-01. Downloaded from https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3610022301. Chained $2007.
Employment Shares	Share of full-time workers by industry	Statistics Canada Table 14-10-0023-01. Downloaded from https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1410002301.
Carbon Tax Rate	Province-level carbon price	BC carbon tax rate from BC Ministry of Small Business and Revenue at https://web.archive.org/web/20130513055926/http:/www.rev.gov.bc.ca/ documents_library/notices/British_Columbia_Carbon_Tax.pdf. AL Specified Gas Emitters Regulation (SGER) price from AL Ministry of Finance documents and set at C$15 per ton of CO2 post-2007. QC carbon price based on average price of QC cap and trade allowance auctions at http://www.environnement.gouv.qc.ca/changements/carbone/ventes-encheres/avis-resultats-en.htm.

Table A3. EU Country Regressions Data Sources

Variable	*Description*	*Source*
GDP	Gross domestic product	OECD data from https://data.oecd.org/gdp/gross-domestic-product-gdp.htm.
Carbon Tax Indicator	Indicator for presence of carbon tax	Data from World Bank (2018).
Emissions Share	Share of GHG emissions covered by carbon tax	World Bank Carbon Pricing Dashboard, https://carbonpricingdashboard.worldbank.org/map_data.

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