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Carbon Taxes[†]

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There is a growing interest in using carbon taxes to reduce greenhouse gas emissions, not only in industrialized economies but also in developing economies. Many countries have considered carbon pricing, including carbon taxes, as policy instruments to meet their emission reduction targets set under the Paris Climate Agreement. However, policy makers, particularly from developing countries, are seeking clarity on several issues—particularly the impacts of carbon taxes on the economy, the distribution of these impacts across households, carbon tax design architectures, the effects of carbon taxes on the competitiveness of carbon-intensive industries, and comparison of carbon taxes with other policy instruments for climate change mitigation. This paper aims to offer insights on these issues by synthesizing the literature available since the 1970s, when the concept of carbon tax was first introduced. This paper also identifies the areas where further investigations are needed. (*JEL* H23, Q35, Q38, Q54, Q58)

1. *Introduction*

In a survey conducted by the Pew Research Center in 2018, 26,612 respondents from 26 countries around the world pointed out that the changing climate due to the global warming caused by increased concentrations of greenhouse gases (GHGs)[1] poses the biggest threat to human civilization (Poushter and Huang 2019). World leaders often reiterate the threat in international forums, such as the World Economic Forum, United Nations meetings, and meetings of civic societies. The World Bank Group considers climate change one of the biggest challenges to economic development in the developing world, particularly in reducing poverty and enhancing shared prosperity (World Bank 2016). The United Nations Development Program (UNDP) considers climate change one of the world's greatest human development challenges (UNDP 2009).

International efforts have been made to combat climate change since the late 1980s. In 1988, the Intergovernmental Panel on Climate Change (IPCC) was established to

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[1] The gases that trap solar radiation (heat) in the atmosphere and cause earth's mean surface temperature to increase. The main GHGs are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6).

synthesize and communicate the knowledge about climate change science, impacts, and mitigation measures. The Rio Earth Summit announced the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 to coordinate and facilitate global efforts in addressing climate change (United Nations 1992). Over the last 28 years, a series of international negotiations took place, and several international agreements have been reached under the UNFCCC, including the Kyoto Protocol in 1997, the Copenhagen Accord in 2009, and the Paris Climate Agreement in 2015.[2]

Academic and research institutions played a major role in understanding the science and impacts of climate change and mitigation measures. One of the key policy instruments to reduce GHG emissions is the carbon tax. The principle of the carbon tax is not new. It follows the environmental tax principle pioneered by the English economist Arthur Cecil Pigou about 100 years ago (Pigou 1920). The Pigouvian principle suggests that negative externalities, such as environmental pollution, emitted during the production of goods and services, should be taxed to avoid or reduce their adverse impacts on society. The private costs of economic activities releasing GHG emissions are distorted because of the exclusion of costs of climate change damages. A carbon tax corrects market distortions by taxing carbon emissions and thereby causing emitters to pay for the social costs.

A carbon tax has been or can be implemented in many forms. For example, a carbon tax can be imposed on fossil fuels in proportion to CO_2 emissions released when the fuel is burned for intermediate or final consumption. This approach penalizes a fuel with higher carbon content, such as coal or petroleum coke, more than fuels with lower carbon content, such as natural gas. A carbon tax can also be imposed on a good or service in proportion to CO_2 emission released during its production. While both forms of a carbon tax have the same purpose—putting a price on CO_2 emissions—they have different implications in terms of a carbon tax design and their effects on an economy.

Although the concept of environmental tax developed almost a century ago, its active discussion in academia started about a half a century ago. In the early 1970s, economists such as William Baumol (Baumol 1972), William Nordhaus (Nordhaus 1977), and David Montgomery (Montgomery 1972) started research on the carbon tax and other carbon pricing instruments, such as the cap and trade scheme. Since the early 1990s, when the international communities showed increased attention to the climate challenge and started initiatives to respond to the problem, more research on carbon tax has also begun. Since then, hundreds of studies have emerged on various issues related to the carbon tax.

In practice, some countries have already introduced the carbon tax. The Scandinavian countries introduced the carbon tax in the early 1990s. Currently, more than 30 economies have introduced carbon tax at the national and subnational levels (World Bank 2020). From the practice perspective, the carbon tax got further attention after the Paris Climate Agreement, where countries made pledges to reduce their GHG emissions, also referred to as their NDCs,

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[2] The Kyoto Protocol mandated that developed countries and economies in transition reduce their GHG emissions, on aggregate, 5.2 percent below their 1990 level by 2012 (United Nations 1998). The Copenhagen Accord recognized that earth's mean surface temperature should not be 2°C higher than the preindustrial level. It recommends 50 percent reduction of global GHG emissions by 2050, along with comprehensive programs for climate change adaptation (United Nations 2009). The Paris Climate Agreement sets long-term targets of maintaining temperature increase at 2°C, preferably 1.5°C above the preindustrial level. All signatory countries made pledges to reduce their GHG reductions by 2030 based on their national circumstances (nationally determined contributions, or NDCs) (United Nations 2015).

by 2030. Eighty-eight countries out of the total 155 signatory countries of the Paris Agreement have considered carbon pricing, including the carbon tax, as a policy instrument to meet their pledges.

The objective of this paper is to communicate to a broader audience, including policy makers, the most relevant knowledge on carbon tax issues synthesizing academic literature developed over the last 30 years. The topics discussed in this review include the rationale for a carbon tax, rate design and revenue recycling, economic and distributional impacts, challenges to its implementation, and lessons learned from the practice. To achieve this objective, I tried to review all academic studies on carbon tax published since 1970. Several databases, such as JSTOR, EconLit, and Google Scholar, are used to retrieve the studies. Keywords used for the literature search are "carbon tax" and "carbon pricing." Since "carbon pricing" also includes literature related to CO_2 cap and trade, I did not include that literature, nor did I include the literature on the shadow carbon price, which refers to the implied unit cost of CO_2 reduction (US$/t$CO_2$) to meet a specified target of emissions reduction. I have listed existing studies in the appendix (table A1), classifying them into various categories, and also indicating the evolution of the literature. Also presented in the appendix is the classification of the analytical methodology used in carbon tax literature.

A few review studies have already discussed various issues related to carbon tax based on existing literature[3]. Analyzing global warming policies from the public finance perspective, Poterba (1993) discusses the basic characteristics of a carbon tax, including its nature, international incidence, and implementation issues. However, since most studies on carbon tax have emerged after the mid-nineties, it does not capture the findings of those studies. Baranzini, Goldemberg, and Speck (2000) discuss some key features of the carbon tax, such as its competitiveness and distributional impacts. The arguments presented are either opinion-based or based on limited studies carried out by then. The most analysis on carbon tax's competitiveness and distributional impacts are carried out after the publication of Baranzini, Goldemberg, and Speck (2000), Ekins and Barker (2001) discuss, in detail, several issues of carbon tax including costs of a carbon tax on the economy, competitiveness of sectors, income/welfare of households by income (distributional impacts), and some design issues of the carbon tax, such as revenue recycling and double dividend arguments. As mentioned above, this study, too, does not capture many empirical insights brought by the studies after 2001.

More recent reviews of carbon tax literature are Aldy (2017), Aldy et al. (2010), Tietenberg (2013), and Marron and Toder (2014). Aldy et al. (2010) briefly discuss some issues related to the carbon tax, particularly the fiscal linkages, distributional considerations, and technological diffusion. However, having a much broader scope covering many issues of climate change policies in general, the discussions specific to the carbon tax are light. Their discussion was based on a few selected studies. Aldy (2017) presents the carbon tax issues, particularly in the context of the US economy. Tietenberg (2013) offers a brief exposure of various issues related to carbon pricing, including the design of pricing instruments and their impacts on economics, CO_2 emissions, renewable energy, technological diffusion, etc. Although the review covered a wider range of issues, the treatment of each issue is brief and introductory. Marron and Toder (2014) briefly discuss two particular issues: tax rate design

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[3] Please see, for example, Poterba (1993); Baranzini, Goldemberg, and Speck (2000); Ekins and Barker (2001); Aldy et al. (2010); Tietenberg (2013); Aldy and Stavins (2012a); and Marron and Toder (2014).

and revenue recycling schemes. They do not discuss many other topics.

This paper aims to shed light on the carbon tax from multiple angles. It dives deeper into the issues, explicitly focusing on carbon tax instead of covering broader issues of climate change mitigation policies considered in the existing review studies. Instead of picking a few selected studies, as practiced in the existing reviews, it covers most carbon tax literature available. It highlights the evolution of the literature, classifying studies based on the issue of investigation and the analytical tools employed. This review article could be very informative for readers to understand the research questions already investigated. It captures insights from the more recent literature not covered in the existing reviews. Finally, it highlights the knowledge gap for future research.

This paper is organized as follows. Section 2 sets the context by discussing the need for the carbon tax to achieve the long- and short-term objectives of the Paris Climate Agreement, highlighting its economic efficiency against other policy instruments. This section also highlights the environmental and fiscal co-benefits. Section 3 briefly summarizes the literature and analytical methods employed. Section 4 synthesizes the experience of the carbon tax from the practice. Section 5 discusses various issues, including macroeconomic and distributional impacts, rate design and revenue recycling, competitiveness, and border tax adjustment. Section 6 highlights the key challenges from the implementation perspective, including political economics, market barriers, and social acceptance. Section 7 points out the main research gaps. Finally, section 8 draws the conclusions. The appendix presents two tables. The first table presents the evolution of the literature, classifying it on issues investigated. The second table lists the existing studies against the analytical techniques they employ.

2. *The Context: Why Carbon Tax?*

Policies to reduce GHG emissions can broadly be divided into three categories: fiscal or pricing policies, regulatory policies, and direct public investment. Pricing policies include instruments such as carbon taxes, emissions trading, subsidies to clean or GHG mitigation technologies, and GHG offset mechanisms. Regulatory policies include various types of mandates such as renewable energy portfolio standards, energy efficiency standards, and vehicle mileage standards. Direct public investment refers to the government's investments in GHG mitigation measures. For example, a government-owned electricity utility company builds solar power plants or implements electricity demand management programs. Governments in lower-income countries often get grants and soft loans from international development agencies and bilateral/multilateral donors to implement GHG mitigation measures.

Most developing countries to date have preferred direct investments in technologies that ensure additional benefits besides GHG mitigation. For example, an investment in energy-efficient technologies could produce benefits (i.e., energy savings) that exceed the costs even if GHG reduction is not taken into account. The increased deployment of renewable energy technologies helps reduce local air pollution besides GHG reduction from the power sector. The other incentive for developing countries to implement direct investment measures is the subsidized finance (e.g., grants, low-interest loans) from their development partners directly or through multilateral development banks. However, as discussed in the next subsection, massive cuts in GHG emissions are needed to meet the long-term objective of the Paris Climate Agreement. Without effective and efficient policies, such as carbon taxes that can drive all economic agents toward reducing GHG emissions, the long-term objective of the Paris Climate Agreement would be difficult to achieve. I also discuss below why a carbon tax is desirable, as compared to other policy instruments for climate change mitigation.

2.1 *Carbon Taxes for Achieving the Paris Climate Agreement*

The Paris Climate Agreement has set up two goals, one for the long term and another for the short term. The long-term goal is to contain the global concentrations of GHGs at the level that does not allow rising of earth's mean surface temperature above 2°C from the preindustrial level. The short-term goal is to ensure commitments from signatory parties to reduce their GHG emissions by 2030. In line with the short-term goal, parties to the Paris Agreement have voluntarily offered pledges to reduce their emissions based on their national circumstances as specified in the NDCs. The Paris Agreement does not prescribe any policy instruments to the parties to meet their NDCs. However, Article 6 of the agreement implies the potential use of market-based mechanisms, including carbon taxes (United Nations 2015). The rules and regulations pertaining to the article are yet to be finalized. Almost 100 economies[4] representing 58 percent of global GHG emissions are considering using carbon pricing, including the carbon tax, as a tool to meet their NDCs (World Bank 2020).

Several studies investigate, from the global, regional and national perspectives, carbon taxes for meeting the Paris Agreement. One set of studies focuses on carbon taxes to achieve the short-term goal (i.e., achieving the NDCs in 2030), whereas the other set of studies analyzes carbon taxes required to meet the long-term objective of the Paris Agreement (i.e., meeting the 2°C targets). For example, Timilsina, Cao, and Ho (2018) examine the required carbon tax rate and its economic implications to meet China's NDC. Chen and Hafstead (2019) do the same for the United States. Studies, such as Dietz et al. (2018) and Guivarch and Rogelj (2017) investigate carbon taxes to meet the long-term objective of the Paris Agreement. Stigliz and Stern (2017) recommend the pathways of carbon taxes until 2050 to achieve the long-term goal of the Paris Agreement. The determination of required tax rates and their economic implications are discussed later. Some other studies that examine the role of the carbon tax to achieve objectives of the Paris Agreement are Gurgel, Paltsev, and Breviglieri (2019) for Brazil; Pradhan, Shrestha, and Limmeechokchai (2020) for Nepal; Wattanakuljarus (2019) for Thailand; and Lee et al. (2018) for Japan.

2.2 *Carbon Taxes versus Other Policy Instruments*

There exists a general consensus among economists that an efficiently designed carbon pricing policy is preferable to nonmarket and regulatory instruments to reduce GHG emissions (Aldy and Stavins 2012b, Metcalf 2009c). Baranzini et al. (2017) summarizes the key reasons behind this consensus: (i) it can cover all sources of emissions, both in the producer and consumer sides; (ii) it addresses the heterogeneity of emitters, thereby lowering the GHG mitigation costs; (iii) it provides the incentive for adoption and innovation of low carbon technologies; (iv) it avoids potential rebound effects that are common in energy-efficient technologies; (v) it prevents carbon leakage (between sectors, in the case of national carbon tax, and between countries, in the case of global carbon tax); (vi) it reduces monitoring and compliance costs; and (vii) it provides incentives to all stakeholders. Regulatory policy instruments, such as mandates and

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[4] Out of 189 economies that ratified the Paris Climate Agreement as of April 2020 (World Bank 2020).

standards, have several limitations. Unlike an upstream carbon taxes, regulatory measures are often heterogeneous across the emitters; they entail higher compliance costs. They do not provide incentives for development, adoption, and diffusion of environmentally and economically superior control technologies (Aldy and Stavins 2012b). Pricing or market instruments are less regressive than nonmarket and regulatory instruments to control environmental externalities (Levinson 2019).

2.2.1 *Carbon Pricing versus GHG Mitigation Regulations*

Several studies have proven numerically that pricing policies are more efficient than regulatory policies to achieve the same environmental outcome. Comparing six different policies (emissions price, emissions performance standards, fossil power tax, renewables share requirement, renewables subsidy, and research and development (R&D) subsidy), Fischer and Newell (2008) show that emissions price is the most efficient single policy for achieving a given level of emissions reduction. The reasons are the same as pointed out by Baranzini et al. (2017), above. Some studies provide quantitative results about the cost efficiency of pricing instruments compared to regulatory instruments (i.e., standards or mandates). Comparing the net societal benefits (including climate change and health benefits) between renewable energy portfolio standards (RPS) and carbon pricing in the US Rust Belt[5] to achieve the same level of GHG mitigation, Dimanchev et al. (2019) show that the net benefit under carbon pricing would be 60 percent higher than that in the RPS case. Reviewing 14 studies that simulate various pricing and regulatory instruments to control environmental pollutants, Tietenberg (2006) reports that the cost of pollution abatement under the pricing instruments would be 40–95 percent lower than that under regulatory or administrative emission control policies. To achieve the same amount of reduction in gasoline consumption and associated emissions, Austin and Dinan (2005) find that the gasoline tax would be 65 percent cheaper than fuel economy standards. Newell and Stavins (2003) find the cost of pricing instruments half of that of performance standards for the same level of emissions reduction in the power sector. Using a two-stage econometric approach to investigate the role of various policy instruments to reduce emission intensity, Adetutu et al. (2020) conclude that a broader policy instrument, such as a carbon tax, would be more efficient than a narrow or specific policy instrument such as energy efficiency improvement.[6]

Pricing or market instruments are better not only from an economic efficiency perspective, but they are also better from a distributional perspective. Levinson (2019), for example, shows that energy efficiency standards are more regressive than energy taxes in the United States. Levinson also finds that the gasoline tax would be less regressive than the fuel economy standards on a revenue-equivalent basis. Davis and Knittel (2019) report similar findings while investigating the distributional effects of US fuel economy standards.

2.2.2 *Carbon Tax versus Emissions Trading*

The debate on carbon taxes versus the emissions trading system (ETS) is the debate between the explicit setting of a price on CO_2

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[5] It includes ten states: Delaware, Illinois, Indiana, Maryland, Michigan, New Jersey, Ohio, Pennsylvania, West Virginia, Wisconsin.

[6] Although pricing instruments are more economically efficient than other policy instruments to reduce GHG emissions, many economists argue that the efficiency indicated by theoretical studies may not be achieved in practice due to various market distortions and political economy factors (Goulder and Parry 2008).

emissions that determines the amount of CO_2 reduction versus defining the amount of CO_2 reduction up front that determines the market price of CO_2. Weitzman (1974) shows that under uncertainty, the choice between these two instruments is determined by the relative slopes of the curves representing the marginal benefit (here, benefit from reducing CO_2 emissions) and the marginal cost (here, the marginal cost of CO_2 abatement). If the marginal benefit curve is flat relative to the marginal cost curve, price control is preferred. On the other hand, if the marginal benefit curve is steeper than the marginal cost curve, quantity control is preferable. Other studies, such as Hoel and Karp (2002) and Newell and Pizer (2003), offer further insights by accounting for dynamic factors (e.g., discounting, stock decay). Hoel and Karp (2002) show that the ranking of the two policies depends on the discount and stock decay rates when environmental damages are caused by the stock of pollution. A carbon tax is favored for a higher discount rate or the higher stock decay rate because it increases the importance of current flows relative to future stock effects. Newell and Pizer (2003) find that if substantial emissions reduction is needed in the short run, which implies a steeper slope of the marginal benefit curve, quantity control is desired. They also show that when the existing stock is large relative to the annual flow (a case of GHG emissions), pricing instruments are preferable so long as the optimal control falls short of stabilization at the current stock level.

In practice, carbon tax and ETS differ significantly due to their design architectures, such as quota allocation rules in the emissions trading scheme and revenue recycling options in the carbon tax. For example, if the emission allowances are auctioned to generate revenue, an ETS would be similar (in terms of its environmental and economic impacts) to a carbon tax, other features unchanged. An ETS is different from a carbon tax if emission allowances are distributed through grandfathering as the former does not generate revenues (Timilsina 2018).[7] A number of qualitative analyses have debated between the carbon tax and ETS.[8] Chief among them are Goulder and Schein (2013); Metcalf (2009a); Aldy (2017b); Aldy et al. (2017); Hafstead, Metcalf, and Williams (2017); and Aldy, Ley, and Parry (2008). Goulder and Schein (2013) argue that there is no fundamental difference between the carbon tax and ETS in terms of burden-sharing and competitiveness impacts if the policies are designed properly. Aldy et al. (2017) and Hafstead, Metcalf, and Williams (2017) contrast carbon tax and ETS in terms of uncertainties involved and offer some suggestions to reduce the uncertainties.

Quantitative analyses measuring the difference in economic impacts between the carbon tax and ETS are rare for a valid reason. As long as the design architecture is the same, both instruments will produce the same results in terms of economic impacts and GHG mitigation (Goulder and Schein 2013). The findings of Goulder and Schein on the key issues of the carbon tax (e.g., economic and distributional impacts, revenue recycling, competitiveness impacts) would be the same as in ETS as long as the initial emission allowances are distributed through auctioning.[9] Any differences in results

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[7] There are many distortions regarding the use of auctioned revenues in practice when emission allowances are distributed through auctioning. In some cases (New Zealand, California) revenues from auctioned allowances used for environmental spending. Cases where the revenues from emission allowances auctioning are used for tax cuts or other macroeconomic purposes very limited.

[8] Wirl (2012) and Karp, Siddiqui, and Strand (2016) analyze a carbon tax and cap & trade system through theoretical models (game theoretic) and suggest that price and tax policies would be more effective than cap & trade for climate change mitigation.

[9] Parry and Williams (2010) examine the efficiency and equity issues of a cap and trade system and find that the cap and trade policy with auctioning all allowances and recycling the revenues to cut income taxes would be most effi-

between the carbon tax and ETS are not from the fact that they are different policy instruments; they might be coming from the difference in design architecture.

The ongoing debate between carbon tax versus ETS has created some confusion for policy makers on selecting these instruments. Several economies, including the Canadian province of Quebec, China, New Zealand, the Republic of Korea, California, and northeastern and mid-Atlantic states in the United States have introduced ETS; the Canadian province of British Columbia, Colombia, Chile, and Mexico have introduced a carbon taxes. Some members of European Union have introduced both (Timilsina 2018).

Timilsina (2018) highlights some practical aspects that help policy makers to weigh ETS versus carbon tax. If not differentiated across the sectors and fuels, and introduced uniformly throughout an economy, a carbon tax is more convenient than ETS to implement. This is because a uniform carbon tax does not require a complex monitoring and verification process, which is essential under the ETS. The initial allocation of emissions allowance in ETS is complex. The monitoring and verification of the allowances are expensive, not only due to high administrative costs but also due to potential legal costs. There is also a perceptional factor that matters. As a tax, a carbon tax could be seen as a burden for industries and households, whereas ETS could be seen as a new market opportunity (Timilsina 2018).

2.3 *Environmental Co-benefits of Carbon Taxes*[10]

A carbon tax reduces not only CO_2 emissions, but also other pollutants emitted from the burning of fossil fuels, such as particulate matters (PM), oxides of sulfur (SO_x), and nitrogen (NO_x), which cause a serious challenge to human health. Reducing harmful local air pollution is an important co-benefit of a carbon tax policy. A recent study for China (Li et al. 2018) estimates health benefits achieved through air quality improvement due to a carbon tax. A US\$72/tCO_2[11] carbon tax that reduces 24 percent of national CO_2 emissions by 2030 also reduce SO_2 and NO_x emissions by 25 percent and 19 percent, respectively. It reduces the national population-weighted annual average $PM_{2.5}$[12] concentration in 2030 by 12 percent from the baseline. The reduction of PM concentration would avoid 94,000 premature mortalities, which is more than the estimated number for the US Clean Power Plan in 2030. The health co-benefits of the PM reductions are 3.7 times larger than the cost of the carbon tax. The study suggests that developing countries, like China, which rely on coal with limited end-of-pipe pollution control, could justify a carbon tax to reduce local air pollution damages to human health. Woollacott (2018) estimate that a US\$25/tCO_2 carbon tax introduced in the United States in 2020 and increased 5 percent annually until 2040 would produce US\$71–162 billion health benefits by reducing local air pollutant,

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cient (or least costly). The policy would be most expensive if the revenue is recycled to households through lump-sum dividends. However, the least costly policy is regressive and the dividend policy is progressive. This finding is similar to what we concluded for carbon tax in this paper.

[10] There exists a rich literature estimating co-benefits, particularly health benefits through reduction of local air pollution, of climate change mitigation in general. However, we have not included those studies here unless they specifically address health benefits (or co-benefits) of carbon tax policy.

[11] tCO_2 refers to tons of CO_2.

[12] $PM_{2.5}$ signifies particulate matter of 2.5 micrometers or less.

$PM_{2.5}$. It would avoid the deaths of 8,559 to 19,329 people. If the carbon tax is doubled (US$50/$tCO_2$), the corresponding health benefits will increase by 35 percent. Parry, Veung, and Heine (2015) estimate the health co-benefits of a carbon tax in the largest 20 emitting countries through the reduction of local air pollution. The countries that can benefit the most from using the carbon tax to reduce local air pollution are Saudi Arabia, Iran, Russia, China, and Poland. The study also suggests that countries with high CO_2 emissions should not wait for international agreement on carbon pricing; instead, they should introduce a carbon tax to reap the associated health benefits.

2.4 *Fiscal Co-benefits of Carbon Taxes*

Besides the climate change and other environmental benefits, a carbon tax could also provide fiscal co-benefits through the additional government revenues it generates. A uniform carbon tax has a broader base, as it covers all sources of carbon emissions. Studies have shown broadening the tax base tends to be more efficient than increasing the tax rate (Dabla-Norris and Lima 2018, Chetty, Looney, and Kroft 2009).

The carbon tax could also avoid tax evasion common in income tax or value-added tax (VAT). It is estimated that the noncompliance rate of VAT varies from 30 percent in the European Union to 60 percent in sub-Saharan Africa (Keen et al. 2015). A carbon tax is difficult to evade because it is imposed on fossil fuels upstream; anyone consuming fossil fuels must pay the carbon tax. In economies where the tax evasion rate is high, the introduction of a uniform carbon tax swapping out the existing VAT or income tax helps fill the revenue gap caused by tax evasion.

Many developing economies are suffering from the predominant existence of the informal sector. The International Labor Organization (ILO) estimates that the informal sector accounts for 2 billion (or 60 percent) of global employment (International Labor Organization 2018); in South Asia, 75–90 percent of the total labor force is in the informal sector, where more than 90 percent of the labor force is in the informal sector in sub-Saharan Africa. A carbon tax can help address this issue in two ways. First, a revenue-neutral carbon tax that partly replaces income or VAT could significantly increase the government revenue because carbon tax, as explained above, cannot be evaded. A carbon tax, thus, brings the informal sector within the national tax system. Secondly, a carbon tax causes a revenue-neutral shift in the tax base toward energy, thereby decreasing the tax burden on goods substituted for by the informal sector (Bento, Jacobsen, and Liu 2018). It can lead to welfare-enhancing substitution from informal labor into the formal sector. A carbon tax could be a better tax instrument than an income or labor tax in economies with a strong presence of the informal sector because an increase in labor tax could cause formal labor to move into the informal sector, thereby causing the labor supply gap in the formal sector.

3. *Carbon Tax Literature*

3.1 *Typology and Evolution of the Literature*

Some topics related to carbon tax attracted more attention from academia and research than others. The critical issues analyzed over the last 30 years are: (i) macroeconomic and sector impacts; (ii) distributional effects; (iii) revenue recycling schemes; (iv) competitiveness and emissions leakage; and (v) comparison with other policies. Literature also sheds light on some specific issues, such as public acceptance of carbon taxes and environmental and fiscal co-benefits. Table A1 in the appendix lists studies published at different time intervals over the last 30 years with the topics they investigate.

Economists started to discuss the potential use of carbon taxes earlier than the international communities began giving attention to the climate change problem. William Nordhaus of Yale University might be the first economist to explicitly discuss carbon taxes for controlling global climate change. In his 1977 *American Economic Review* paper, he explains the economic consequences of climate change and advocates for carbon taxes as a mitigation policy (Nordhaus 1977). Researchers started to pay more attention to the carbon tax and other policy instruments when the international debate on climate change intensified with the establishment of international institutions, such as the UNFCCC, to respond to this global challenge. The early research (1990-2000), which is more theoretical, address issues such as rate design (static versus dynamic), geographical coverage (national versus international), and efficiency of the carbon tax (See tables A1 and A2). This is followed by a series of studies with numerical techniques, mostly computable general equilibrium (CGE) models, to investigate the economic consequences at national and international levels. One of the most popular issues discussed during the late nineties was the revenue recycling scheme and the "double dividend hypothesis" suggesting that an environmental tax, such as a carbon tax, can have two benefits. First, it reduces environmental pollution; secondly, it helps lower the distortions caused by existing taxes on factors and goods (Goulder 1995a; McKitrick 1997; Parry, Williams, and Goulder 1999; Parry and Bento 2000).

Compared to other periods, the 2000–2010 period did not observe many studies. This was the same period when climate change negotiation was not taking a concrete direction, as the major players (the United States and Canada) stayed out of the milestone climate change agreement, the Kyoto Protocol. Two new issues related to climate change got attention in this period: (i) the comparison of a carbon tax with other policy instruments, such as tradable permits, R&D investment, and subsidies to clean technologies; and (ii) the distributional impacts of carbon taxes by household income level (see table A1 in the appendix).

Research on carbon taxes intensified after the year 2010, when climate change negotiation entered into a new active phase with the Copenhagen Climate Accord, agreed upon at the end of 2009. Since issues like distributional impacts, competitiveness, and border tax adjustment and revenue recycling were still the central issues of research, more studies focusing on these issues emerged (see table A1). Also investigated after 2010 were environmental co-benefits, public perception toward the carbon tax, and comparison of a carbon tax with other policies (ETS, renewable energy standards, energy efficiency standards). Several carbon tax studies published after 2010 also focused on a particular sector, such as the transport sector, the power sector, and the forestry sector. When the Paris Climate Agreement was reached in 2015, researchers jumped to investigate the role of the carbon tax in achieving the long-term (1.5 degree and 2 degree targets) and short-term goals (NDCs) of the Paris Agreement (table A1).

3.2 *Analytical Methods Used in the Literature*

Existing studies have used different methodologies to analyze issues related to the carbon tax, including theoretical, numerical, empirical (econometrics), and qualitative techniques. The numerical models used to investigate carbon tax issues can be divided into multiple groups based on the methodology, such as CGE models, input–output (I-O) models, partial equilibrium models, and optimization models. The CGE model is the most common analytical tool used to analyze most issues related to the carbon tax. Table A2 in the appendix lists the existing studies under various methodological categories.

The selection of an analytical tool depends on the objective of a study. In the early years (i.e., the 1990s) many studies used theoretical approaches. These studies investigate questions that are generic across countries and economic sectors. Over the last 30 years, the body of carbon tax literature expanded exponentially; however, those using theoretical approaches are limited and declining. While theoretical models are normally robust in predicting qualitative results (i.e., whether a carbon tax increases or decreases welfare), they cannot predict the magnitude (e.g., the percentage change in GDP or welfare). Policy makers tend to be more interested in quantitative results. A carbon tax affects economic agents (i.e., households, firms, governments) differently; its impacts vary across production sectors (e.g., agriculture, electric power generation, the service sector). Numerical models are therefore needed to measure these quantitative impacts. The choice between theoretical versus empirical models is not one of superiority in terms of quality of one approach versus the other, rather it is the objective of the research question at hand. The increased popularity of the CGE approach to analyze carbon taxes is based on its suitability to measure the quantitative impacts, which are heterogeneous across sectors and agents. Not only studies for developed countries but also a large number of studies for developing countries have used CGE models to analyze the carbon tax (see table A2)[13].

Some studies (please see table A2) also use I-O models to analyze carbon tax issues. I-O models are structurally similar to CGE models as both use I-O tables. They are, however, significantly different in many respects.[14] CGE models are flexible in choosing functional forms to represent agents and allow substitutions between factors, between factors and intermediate inputs, and between intermediate inputs themselves. I-O models use fixed coefficients (or the Leontief functional form) and do not allow substitution possibilities in response to price changes. Moreover, I-O models are not capable of reflecting supply constraints.

Partial equilibrium models are flexible, like CGE models. However, they are different from the CGE model in many respects. The coverage of economic agents in a partial equilibrium model is not as extensive as in CGE models. Partial equilibrium models model the behaviors of some agents while fixing the others, and therefore fail to capture the interactive effects of economic agents in response to a policy shock. Partial equilibrium models are used when the analysis focuses on particular sectors, such as agriculture, forestry, and electricity sectors (table A2). Optimization models are found to be used mainly to analyze the impacts of a carbon tax on the energy supply mix in a country or the fuel mix in its power generation system (see table A2). They use an optimization technique to find the least-cost energy supply mix or electricity generation mix for a given period in the future, satisfying technological, environmental, and other constraints. Econometric methods are used for two purposes: First, to observe the impacts of the carbon tax on fuel or CO_2 emissions in countries or regions where a carbon tax has been introduced for many years. Second, it is used to analyze stakeholders' or public opinion about carbon tax policies. It is also used to examine if a carbon tax makes an economy

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[13] Detailed description of CGE modeling is beyond the scope of this paper. Interested readers could refer to Shoven and Whalley (1984) and Dixon and Jorgenson (2013).

[14] Rose (1995) provides a good account of differences between these two types of models.

where it has been introduced worse off (table A2).

4. *Carbon Tax in Practice*

Despite the extensive research on the carbon tax, the implementation of a carbon tax in practice is limited. However, policy makers' perceptions toward it is changing, and its implementation in recent years has increased. As of 2020, more than 30 economies (including subnational) have introduced carbon taxes worldwide. Based on World Bank (2020), figure 1 shows timeframes during which carbon taxes were introduced and the current levels of carbon taxes in different economies. Nordic countries introduced the carbon tax in the early 1990s. Currently, their carbon tax rates are the highest in the world. About three-quarters of emissions covered by existing carbon pricing schemes are priced at less than US\$10/tCO_2e, much smaller than the level required to achieve the Paris Agreement (World Bank 2020).

Although the economic theory suggests that a carbon tax would be most efficient to reduce GHG emissions if the tax rate is uniform across the economic sectors and it has a wider base (Oates 1995, Hoel 1996, Marron and Toder 2014), implementation of a carbon tax in practice is often distorted. Some sectors (in some cases, carbon-intensive ones) are exempted for various reasons. The rates are very low (e.g., US\$1/tCO_2 in Poland and Ukraine although they introduced carbon taxes many years ago). Considering the political appetite and acceptability to consumers, all economies that have introduced carbon taxes moved very carefully to implement this policy. They kept the initial tax rate small and sectoral coverage limited. The rates have been gradually increased, and sectoral coverage has been expanded over time. For example, in British Columbia, when the carbon tax was introduced in July 2008 the rate was small, CN\$10/tCO_2; it was increased by CN\$5/tCO_2 per year until 2012 when it reached CN\$30/tCO_2, and since then it has remained constant (Rivers and Schaufele 2015). When the carbon tax was introduced in January 1991 in Sweden, the rate was US\$40/tCO_2; industrial users were allowed to pay only half of the rate and certain energy-intensive industries, such as mining and horticulture, were completely exempted (IEA 2008). Currently, the Swedish carbon tax rate has reached US\$119/tCO_2 (i.e., more than three times higher than the initial rate). Recently, several Latin American countries have introduced a carbon tax. They have started with a low rate, US\$ 3–6/tCO_2. Chile's carbon tax is for the electricity sector only, whereas Mexico's carbon tax covers all sectors, but it excludes natural gas, the country's main fossil fuel source (Narassimhan et al. 2018). In Colombia, the carbon tax covers only the petrochemical and refinery sectors.

Carbon tax revenue schemes vary across countries where there is a carbon tax. Some economies (e.g., Sweden, Finland, Norway, and British Columbia) recycle the carbon tax revenues to partially offset personal and corporate income taxes, while others recycle the revenues for various purposes. Denmark recycles 40 percent of carbon tax revenue to subsidize environmental programs and the rest is returned to industries. Part of carbon tax revenue is used to finance the green home program and health insurance in Switzerland. In Chile, it is allocated for education and social programs.

Although the carbon tax has been in practice for over the last 30 years in some countries (e.g., Nordic countries), it is gaining international attention more recently, particularly after the 2015 Paris Agreement. Politicians who were reluctant to consider carbon taxes due to potential resistance from consumers or adverse implications to their voter base started to take on the challenge

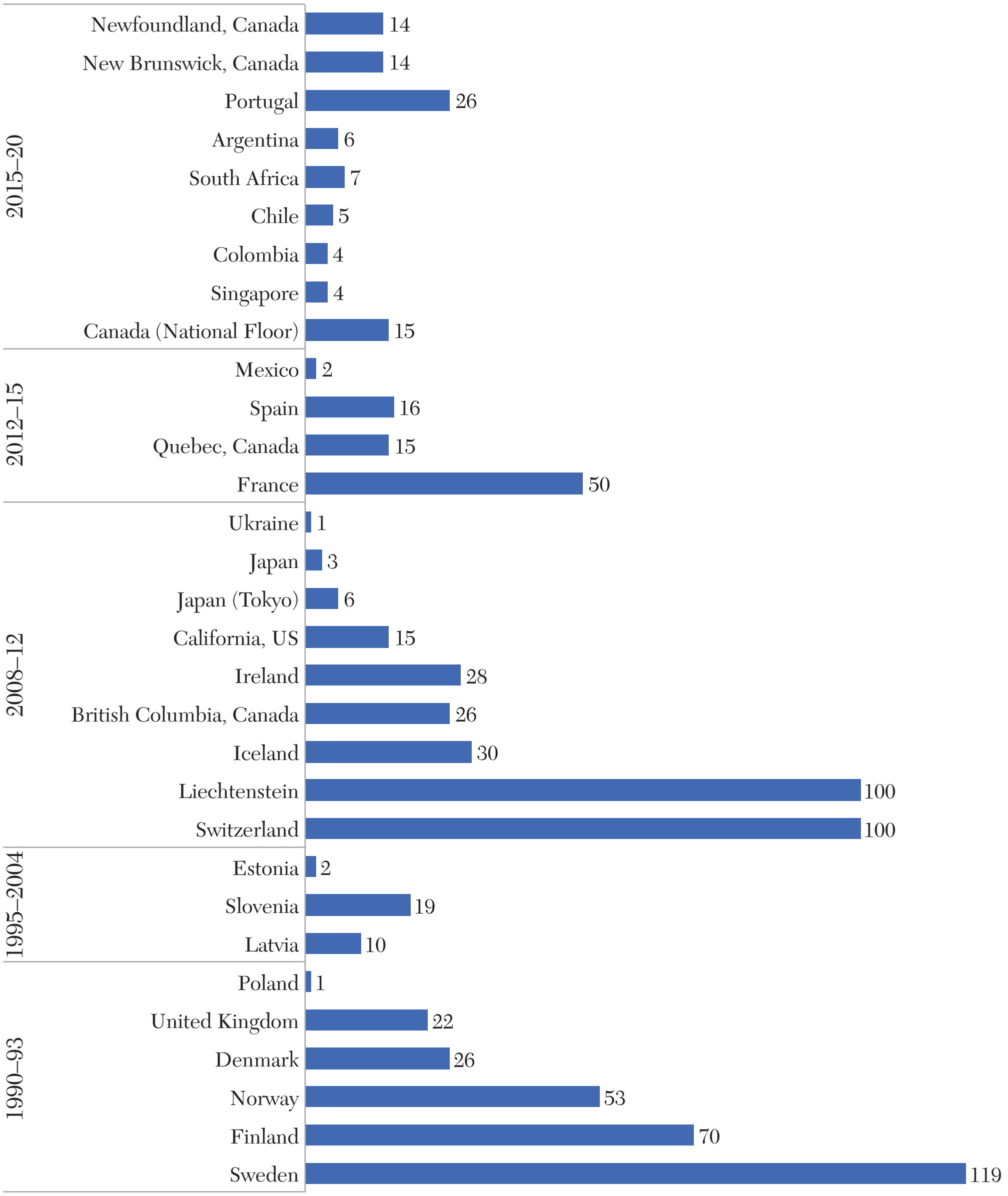

Figure 1. Carbon Tax Introduced in Practice (2020 US$ per tonne of CO_2)

Notes: Tax rates vary in some countries. The numbers presented here are the upper values. These are the rates as of 2020; rates at the time of introduction could be different.

Source: World Bank (2020).

of discussing the carbon tax and ultimately introducing it. The large pool of knowledge on the carbon tax and its communication to policy makers might have contributed to its increasing political acceptability.

5. *Key Issues of Carbon Taxes*

In this section, I elaborate on the primary issues of carbon taxes discussed in the literature: macroeconomic and distributional impacts, tax rate design, revenue recycling, competitiveness, and border tax adjustment.

5.1 *Overall Economic Impacts*

A large number of studies have measured potential economic loss due to a hypothetical (in some cases actual) carbon tax. Earlier studies concluded that a carbon tax causes an economic loss (i.e., GDP or welfare loss) unless the benefits of climate change mitigation are quantified and accounted for. This is because a carbon tax causes the economy to shrink, reducing sectoral economic outputs (e.g., sectoral outputs) and national economic output (GDP), international trade, and household welfare. However, some studies find that a carbon tax could cause economic gain if the carbon tax revenue is invested in efficient, productive sectors or used to cut existing capital tax (e.g., McKibbin et al. 2015, Jorgenson et al. 2018, Ross 2018). Analyzing the relationship between an existing carbon tax and key economic indicators (e.g., GDP, employment), some recent studies also show that carbon taxes do not impact the economy negatively. Using an econometric method to investigate the relationships between the existing carbon taxes and GDP and employment in EU countries, Metcalf and Stock (2020) find no robust evidence of a negative effect of the carbon tax on employment or GDP growth.

The magnitude and direction of economic impacts depend on how the revenues from the carbon tax are recycled into the economy. The economic effects of a carbon tax are sensitive to the structure of the economy and the available energy supply mix. A relatively carbon-intensive economy, due to heavy reliance on carbon-intensive fuels (e.g., coal), faces a larger economic loss than a country with a less carbon-intensive energy supply system. Countries such as China, India, and South Africa are likely to face higher GDP cuts for a given carbon tax rate than France and Norway. This is because the former more heavily rely on coal, a high carbon content fuel, than the latter. Similarly, if low-carbon or no-carbon fuels are available or can easily be imported into an economy, a carbon tax would efficiently cause substitution of high-carbon fuels with low- or no-carbon fuels. Such an economic inter-fuel substitution possibility implies a lower cost of the carbon tax. For example, the cost of a carbon tax in the US economy is expected to be low as the gas price has dropped, and a small carbon tax would trigger a massive substitution of coal-fired power plants with gas-fired power plants. It is already happening even without a carbon tax, especially when investors make a fuel choice while building new power plants. The degree of substitution, however, depends on the rate of the carbon tax relative to costs of competing fuels (e.g., coal and gas for power generation), and stringency of climate policies, et cetera. A larger number of studies analyzing the economic impacts of a carbon tax are listed in table A1 in the appendix.

5.2 *Revenue Recycling Schemes*

A carbon tax generates, depending upon the tax rate, a large amount of government revenue. Recycling of this revenue influences the economy significantly. A rich literature, both theoretical and empirical, is devoted to examining the revenue recycling effects of a carbon tax. There are several schemes to recycle the carbon tax revenue considered in the literature. These include increasing public expenditure, transferring funds to households as a lump-sum rebate[15] (or direct cash transfer), using it to cut existing taxes (e.g., labor tax, capital tax, taxes on goods and services, corporate income tax), investing in export-oriented industries or sectors with higher economic multipliers, and subsidizing cleaner or green technologies.

The most common revenue recycling approaches discussed in the literature are lump-sum transfers to households and cutting existing taxes. Compared with the no-recycling case, where the government uses it for public administration, transferring tax revenue to households as a lump-sum rebate reduces the cost of a carbon tax. Several studies report this finding. For example, Mahmood and Marpaung (2014) show that a US\$50/tCO_2 carbon tax would cause 2.3 percent of GDP loss in Pakistan when the tax revenue is not recycled (i.e., used by the government as before); the GDP loss drops to 1.5 percent if the tax revenue is recycled to households as a lump-sum transfer. Similarly, Meng, Siriwardana, and McNeill (2013) show that a AS\$23/tCO_2 carbon tax causes 0.59 percent GDP loss in Australia when tax revenue is not recycled; the GDP loss drops to 0.48 percent when the tax revenue is recycled to households through a lump-sum rebate.

The cost of a carbon tax with revenue recycled to cut existing taxes would be smaller than when the revenue is transferred to households as a lump-sum rebate. Several studies provide numerical evidence of this. For example, Timilsina, Cao, and Ho (2018) show that a carbon tax (US\$24.2/tCO_2) needed to meet China's pledges under the Paris Agreement (up to 65 percent reduction of China's emissions intensity in 2030 from the 2005 level) would reduce China's GDP in 2030 by 1.19 percent from the baseline if the tax revenue is recycled to households as a lump-sum rebate. The GDP loss drops to 0.74 percent if the carbon tax revenue is used to cut income tax rates. Several studies (e.g., Jorgenson et al. 2018, Ross 2018, Zhu et al. 2018, Caron et al. 2018) conclude that a carbon tax with recycling the tax revenue to cut existing labor or capital taxes would cause lower economic costs than the carbon tax with the lump-sum transfer of tax revenues to households.

The efficiency of a carbon tax can critically hinge on productive use of the revenues. A combination of feebates or regulations that promote most of the behavioral responses under carbon tax can be more cost effective than a carbon tax with lump-sum replacement. The carbon tax causes a much larger tax-interaction effect than the regulatory/feebate approach due to its first-order impact on energy prices and under lump-sum replacement that is not counteracted by an efficiency gain from revenue recycling. Jorgenson et al. (2018) and Ross (2018) support this argument. Jorgenson et al. (2018) find that a carbon tax of \$50/tCO_2 introduced in 2020 and annually increased by 1 percent until 2050 would increase annual GDP by 0.17 percent on average during the 2020–2050 period. Similarly, Ross (2018) shows that if the tax revenue is recycled to cut capital tax, a carbon tax of \$25/tCO_2 introduced in 2020 and annually increased by 5 percent until 2050 would start increasing GDP from 2030.

Several studies (Goulder 1998; Goulder, Parry, and Burtraw 1997; Parry 1997) provide explanations of why a carbon tax's economic cost is lower when it is used to cut existing taxes than when it is transferred to households as a lump-sum rebate. Aldy et al. (2010) further elaborate on this issue. These studies suggest that when a carbon tax is introduced to an economy where existing taxes, such as income taxes, have already

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[15] A per capita or per household cash payment.

created distortions in the factor markets, the carbon tax further exacerbates the distortions. This effect is called the tax interaction effect. Revenues from the carbon tax can be used to partially reduce these marginal distortions (i.e., incremental distortions caused by the carbon tax) by recycling it to cut marginal rates of factor tax in a way that total government revenue remains neutral. Aldy et al. (2010) highlight two points in this regard: how much of the cost of an environmental tax could be offset by recycling the carbon tax revenue to cut factor tax rates and how many inaccuracies or errors are introduced in the estimation of the cost of a carbon tax if the preexisting distortions are ignored.

The public finance literature has emphasized that the full distortions from income taxes extend well beyond those in factor markets. For example, income taxes promote informality, promote excessive compensation in the form of untaxed fringe benefits (like medical insurance in the United States) and create a bias toward tax-favored goods or activities (like housing). As a result, the marginal excess burden of taxation, and the efficiency gains from revenue recycling, can be larger than implied by studies that only capture tax distortions in factor markets.

Many other schemes for carbon tax revenues are analyzed in the literature or introduced in practice. These include recycling carbon tax revenues for subsidizing clean or green technologies to encourage a further reduction of GHGs and local air pollutants, to compensate energy-intensive trade-exposed industries to address their competitiveness. For example, in the recent carbon tax system designed for the liquefied natural gas (LNG) facilities in the Canadian Province of British Columbia, carbon tax revenues will be recycled to accelerate the deployment of innovative clean technologies to reduce GHG emissions (World Bank 2020). Unlike the cases where carbon tax revenues are recycled to cut existing distortionary taxes, using carbon tax revenue to subsidize clean technologies (such as solar and wind power for generation of electricity and efficiency improvements of energy-utilizing technologies) does not lower the economic costs of the carbon tax. Instead, it would further increase the costs, as recycling the revenue from one distortionary policy (i.e., carbon tax) to finance another distortionary policy (i.e., clean technology subsidy) exacerbates the economic distortions. Zhu et al. (2018) include recycling carbon tax revenue to subsidize renewable energy in the United States with other options such as lump-sum transfers to households, labor tax cuts, capital tax cuts, and providing subsidies to investments and find that recycling tax revenue to finance renewable energy subsidy is the most expensive option, as it causes the highest GDP loss. Timilsina, Csordas, and Mevel (2011) find that if part of the revenues from a carbon tax on fossil fuels is used to subsidize biofuels, it significantly helps to expand the latter, but also causes additional GDP loss on top of what the carbon tax has already caused.[16] Although recycling carbon tax revenue to subsidize clean energy would not be efficient compared to recycling the revenue to households through lump-sum transfer or income tax cuts, financing clean energy subsidy through carbon tax revenue would be more efficient than financing it through an electricity price hike. Galinato and Yoder (2010) examine a scheme where energy sources with high emissions to energy price ratios are taxed, and the tax revenue is used to subsidize sources with low emissions to energy price ratios. The study finds that the

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[16] The studies considering the carbon tax revenues for subsidizing renewable or clean energy sources do not account for the external benefits of renewable or clean energy (environmental benefits and learning-by-doing benefits). Using carbon tax to subsidize renewables is less efficient than recycling the revenue to households through lump-sum transfers. If the external benefits are accounted for, the ranking could change.

tax/subsidy program would increase welfare as compared to a no-tax scenario. If the subsidies for low-emitting energy sources are funded through general taxes instead of the emissions tax it would cause further welfare loss.

Some studies also consider using carbon tax revenue to reduce debt (Jorgenson et al. 2015; McKibbin et al. 2015; Tuladhar, Montgomery, and Kaufman 2015). The results in these studies are different for the same tax rate of US\$15/tCO_2. Jorgenson et al. (2015) and Tuladhar, Montgomery, and Kaufman (2015) find that recycling carbon tax revenue to cut the budget deficit would be better than transferring it to households as a lump-sum rebate. On the other hand, McKibbin et al. (2015) find the reverse is true.[17] All three studies, however, show that recycling carbon tax revenue to cut labor or capital tax would be more economical, as compared to recycling it to households as a lump-sum transfer or using it to cut the government deficit.

Based on the literature, one could roughly rank revenue recycling schemes in terms of their cost-efficiency (i.e., impacts on either GDP or welfare). Recycling tax revenues to investment or cutting capital taxes or corporate income taxes are the best options on efficiency grounds, as they could cause economic gains (i.e., GDP or welfare increase), and even if they cause economic loss, that loss would be the smallest as compared to that in other schemes of revenue recycling (McKitrick 1997, Jorgenson et al. 2015, Jorgenson et al. 2018, Ross 2018, McKibbin et al. 2015). Using carbon tax revenue to cut labor tax comes next, followed by transferring it to households as a lump-sum rebate. Using carbon tax revenues to cut government debt, subsidize clean technologies, or increase public expenditures are the most expensive options for recycling carbon tax revenues to the economy. Note that public expenditure here includes only the government's regular expenditure on salaries and wages of government employees or expenditures on internal security and defense. Public expenditure referred to here does not include public investment in infrastructure or human capital.

5.3 *Equity or Distributional Consideration*

One of the key concerns in relation to the carbon tax is its potential regressive impacts, meaning that it disproportionately impacts poor households[18] (Fremstad and Paul 2019; Williams et al. 2015; Mathur and Morris 2014; Verde and Tol 2009; Callan et al. 2009; Baranzini, Goldemberg, and Speck 2000). This is because a carbon tax causes energy prices to increase, and poor households have a relatively higher expenditure share on energy consumption (Fullerton, Heutel, and Metcalf 2012; Marron and Toder 2014; Callan et al. 2009). Fremstad and Paul (2019), for example, find that the richest American households emit more than five times higher CO_2 levels than the poorest American households, yet a carbon tax would cost poor households at higher proportions (i.e., a higher percentage of their incomes) than the rich.

Existing studies analyzing the distributional impacts of carbon taxes concur that the regressivity of a carbon tax can be reduced by transferring the carbon tax revenue to low-income households (Fremstad

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[17] This finding is, however, counterintuitive. A lower carryover of debt means future taxes on labor and capital will be lower, implying an efficiency gain.

[18] In the distributional analysis of carbon tax, where changes in household income or welfare due to the carbon tax are measured by income group or quintile, a carbon tax is considered regressive if the welfare loss increases as the household income decreases (i.e., higher-income households face lower welfare loss as compared to low-income households). A carbon tax is considered progressive if this trend reverses (i.e., low-income households face lower loss of welfare as compared to higher-income households) (Poterba 1993).

and Paul 2019, Callan et al. 2009, Verde and Tol 2009, Gonzalez 2012, Jiang and Shao 2014, Renner 2018, Caron et al. 2018). As discussed above, the impacts of a carbon tax on aggregate (economy-wide) welfare would be worse when the carbon tax revenue is transferred to households as a lump-sum rebate than when it is used to cut existing taxes. This is, however, untrue in the case of distributional impacts of the carbon tax. Low-income households would benefit more when carbon tax revenue is recycled as a lump-sum rebate than used to cut existing taxes. Fremstad and Paul (2019) find that the regressivity of carbon tax can be reversed (or made progressive) if the carbon tax revenue is recycled to households through a lump-sum rebate (equal payment per head). Specifically, they find that recycling carbon tax revenue to cut existing labor taxes reduces the income of 90 percent of Americans in the poorest decile, whereas it increases the income of 98 percent of people in the poorest decile if the carbon tax revenue is transferred to households in a lump-sum manner. Similarly, Williams et al. (2015) show that the lump-sum rebate would increase the welfare of the lowest three quintiles of households (out of five), thereby making the carbon tax policy progressive (i.e., the carbon tax either increases the welfare of low-income households from the baseline or higher reduction of welfare loss as compared to that of high-income households)[19]. The authors find that recycling revenue to cut capital tax exacerbates its regressivity. Mathur and Morris (2014) show that even if only 11 percent of carbon tax revenue is transferred to the poorest two deciles of households, the carbon tax will not cause a loss of their aggregated welfare. On the other hand, if carbon tax revenue is used to cut existing taxes, a cut in the corporate income tax would be relatively more regressive than that in personal income taxes.

Further evidence is provided by Caron et al. (2018), which summarizes the findings of distributional impacts simulated by several CGE models under the Standard Energy Modeling Forum exercise 32 that evaluates carbon taxes in the United States under alternative revenue recycling schemes. Based on model results from most of the CGE models used in this exercise, Caron et al. (2018) conclude that the lump-sum transfer scheme which is the most inefficient or expensive on cost-efficiency grounds (highest economic and welfare loss) would be the most progressive on equity or distributional grounds, as it benefits (or causes minimum costs) to lower-income households as compared to high-income households. On the other hand, a capital tax cut, which is the best revenue recycling scheme from a cost-efficiency perspective, would be the most regressive from an equity perspective.[20] Other studies, such as Klenert and Mattauch (2016) and Mathur and Morris (2014), also report similar findings.

Within a country, a uniform carbon tax could have differing impacts across the regions (states or provinces). Williams et al. (2014) find, in the United States, that if the carbon tax revenue is recycled to cut existing capital tax, it would benefit the richer states (i.e., states with large shares of capital income) more than poorer states. On the other hand, if the tax revenue is recycled to households through a lump-sum rebate, it favors relatively low-income states. In China, Zhang et al. (2019) find that a carbon tax with tax revenue recycled to cut production tax would benefit those provinces (i.e., they

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[19] At the aggregated level, however, the finding is opposite—the aggregated household does much worse due to the carbon tax when carbon tax revenue is recycled through a lump-sum rebate as compared to when the revenue is recycled to cut labor or capital tax rates.

[20] This finding may not necessarily hold true for other economies.

would receive more production tax rebates) that are bigger in terms of production tax payments (e.g., Beijing, Shanghai, Zhejiang, and Jiangsu). On the other hand, a carbon tax with tax revenues recycled to low-income households benefits the central and western provinces, which are relatively poorer.

Studies that analyze the racial inequality of carbon taxes are rare. Intuitively, one could argue that the lump-sum rebate would be preferable to avoid the racial inequality of carbon tax. Fremstad and Paul (2019) show that the lump-sum transfer of carbon tax revenues to households benefits disadvantaged groups, including Black people, Hispanic people, elderly people, and people living in rural areas.

Some studies also analyze the distributional effects of carbon taxes between the present and future generations using general equilibrium models representing overlapping generations (Rausch and Yonezawa 2018, Fried 2018). Rausch and Yonezawa (2018) show that the welfare loss faced by the generations born before the tax is introduced would be smaller than that future generation would face if tax revenue is not recycled. However, the impacts for distant future generations decrease over time. For future generations (those born after the introduction of the tax) welfare loss would be the smallest when carbon tax revenues are used to cut capital tax, and it would be highest when the tax revenues are recycled to households as a lump-sum rebate. For generations born before the tax was introduced, lump-sum recycling schemes favor older generations and income tax cuts favor younger generations. Similar results are reported by Fried (2018), who find that recycling carbon tax revenue through a lump-sum rebate would be favorable to generations born before the carbon tax is introduced, and recycling revenue to cut income tax would be favorable for those born after the introduction of the carbon tax. Fried et al. also show that the regressivity of the carbon tax differs between the generations; the lump-sum rebate scheme is found progressive, whereas the income tax cut scheme is regressive. Based on the findings, Fried et al. argue that carbon tax design should also consider near-term welfare effects instead of focusing only on long-term effects. Analyzing the distributional effects of a carbon tax in the United States using alternative measures for economic welfare, Hasset, Mathur, and Metcalf (2009) conclude that carbon tax would be far less regressive when the lifetime income is used to measure economic welfare than when the annual income is used to measure the welfare.

The distributional impact is a critical issue in jurisdictions where a carbon tax has already been introduced. In British Columbia, where a carbon tax was introduced in 2008 and carbon tax revenue is being used to cut existing tax rates, rural households in the north of the province, which are relatively poor compared to urban households in the south of the province, protested against the existing revenue recycling scheme (i.e., using carbon tax revenues to cut income tax), claiming that they have been disproportionally burdened by the carbon tax because of their higher demand for heating fuels (cold climate) and gasoline (more need for driving) than the households in the province's urban centers in the south. This protest led the provincial government to adjust the tax recycling scheme by introducing the Northern and Rural Homeowner Benefit Program that made a provision of 6–7 percent of carbon tax revenue to transfer to eligible households. Using a CGE model of Canada, Beck, Rivers, and Yonezawa (2016), however, do not find any evidence to support this program due to the small fraction of revenue recycled to the households as a lump-sum transfer.

The impacts of a carbon tax on households are transmitted through multiple channels such as commodity prices, factor prices, income taxes, and government transfers. Dissou and Siddiqui (2014) compare these effects caused by commodity prices versus factor prices and show that a carbon tax's impacts on factor and commodity prices have opposing inequality effects. Inequality drops due to the impacts of a carbon taxes on factor prices; the reverse would be true due to the impacts of a carbon tax on commodity prices. Their conclusion is that the carbon tax has a U-shaped (non-monotonic) relationship with inequality.

Some economists argue that carbon taxes could be used to finance global infrastructure and inequality gaps (Jakob et al. 2016; Davies, Shi, and Whalley 2014). Analyzing a scenario that considers limiting global warming to below 2°C, Jakob et al. (2016) find that revenues from domestic carbon taxes could significantly contribute to close existing access gaps for water, sanitation, electricity, and telecommunication. If the revenues of a global carbon tax are redistributed through the Green Climate Fund (GCF), infrastructure access could be further expanded in developing countries. Davies, Shi, and Whalley (2014) estimate that a 100-year global carbon tax path for the 2015–2115 period, needed to stabilize global emissions such that temperatures do not rise 2°C above the preindustrial level before 2105, can generate enough revenues to improve the global Gini coefficient by 3 percent and to raise the income share of the bottom decile by 81 percent, on average, from 2015 to 2105 if the revenue is distributed across countries on a per capita income basis.

5.4 *Competitiveness and Border Tax Adjustment*

The concern of losing competitiveness of domestic industries, especially the emissions-intensive trade-exposed (EITE) industries, is one of the main factors in pushing back the carbon tax (Böhringer et al. 2017; Böhringer, Rosendahl, and Storrøsten 2017; Gray and Metcalf 2017; Metcalf 2014). This concern arises when a country introduces a carbon tax, but other countries producing competing goods do not. The risks of losing competitiveness undermine political support for a carbon tax (Aldy 2017). The loss of competitiveness causes industries to move to locations where a carbon tax is absent or has a low rate (Jaffe et al. 1995). Several studies have measured the potential competitiveness loss due to carbon taxes. Using a two-step, empirical analysis with 35-year panel data of 450 manufacturing industries in the United States, Aldy and Pizer (2015) find that a carbon tax causes larger output drops of energy-intensive industries due to a higher increase of their relative prices. A carbon tax causes imports of energy-intensive goods to increase and their exports to decrease, thereby deteriorating trade balance. For example, Lu, Tong, and Liu (2010) find, in China, that a carbon tax of 300 yuan (US$40) per ton of CO_2 would cause a more than 3 percent drop in total exports from the baseline. For about the same level of the carbon tax rate (US$40/t$CO_2$), Mahmood and Marpaung (2014) find a more than 4 percent drop in total exports (compared to that in the baseline) in Pakistan. In Mexico, Rivera et al. (2016) show that a carbon tax of US$100/t$CO_2$ would cause total exports to drop by more than 2 percent. Coxhead, Wattanakuljarus, and Nguyen (2013) find that a unilateral environmental tax hurts Vietnam's competitiveness in global markets, not only for energy-intensive industries but also for labor-intensive export industries, as it would impede job growth in the economy.

A unilateral carbon tax causes competitiveness loss and is less effective in reducing emissions due to potential emissions leakage. Emissions leakages occur through two channels: (i) movement of emissions-intensive production from countries with more stringent environmental regulations to countries with no or less stringent environmental regulations, and (ii) the energy market channel (Fischer and Fox 2012; Baylis, Fullerton, and Karney 2013; Aldy and Stavins 2012a; Arroyo-Currás et al. 2015). The potential of emissions leakage through the first channel occurs when a carbon tax unilaterally imposed in a country or a region, emission-intensive firms (e.g., iron and steel, cement) face higher costs due to increased energy prices. These industries would relocate the existing plants in countries and regions where the carbon tax does not exist. Even if relocation of existing plants is too expensive, further expansion of their business could move to locations where a carbon tax is absent or less stringent. Emissions leakage through the second channel occurs when a price drop of fossil fuels due to demand cut in response to climate change mitigation policies encourages countries without climate change mitigation policies to increase their fossil fuel consumption. For example, Arroyo-Currás et al. (2015) show that up to 15 percent of total emissions reduction would leak from EU countries to the rest of the world (e.g., China, India, United States, Middle East) when the European Union introduces its 2050 climate change mitigation road map and other countries do not introduce stringent mitigation policies. Reviewing existing literature, Aldy et al. (2010) report that as much as 15–25 percent of emission reductions achieved through a unilateral carbon tax in the United States could leak elsewhere. Elliott et al. (2010) show that 20 percent of the emissions reductions achieved in industrialized countries through a carbon tax of US\$29/tCO_2 would be offset by emissions leakages to developing countries. Baylis, Fullerton, and Karney (2013) find that emissions leakage could exceed the domestic emissions reduction achieved by a unilateral carbon tax.

Since the loss of competitiveness of EITE industry is the major impediment to carbon tax policies, many studies have investigated different approaches to address this concern. The first approach is to address the problem from the source by taxing imports from countries that do not contribute to global efforts to combat climate change by introducing an efficient policy, such as a carbon tax. This type of tariff on imports is commonly known as "border tax adjustment" (BTA, also referred to as border carbon adjustment or BCA) in the literature (Böhringer, Balistreri, and Rutherford 2012; Clarke 2010; Lockwood and Whalley 2010; Elliott et al. 2010). Summarizing the findings of several studies included in the twenty-ninth modeling exercise of the Standard University-based Energy Modeling Forum (EMF), Böhringer, Balistreri, and Rutherford (2012) report that BCA is a prominent means to reduce emissions leakage and improve the global cost-effectiveness of a unilateral carbon tax. A large literature investigates the impacts of BTA/BCA (see, e.g., Gentry 2017; Tang et al. 2015; Keen and Kotsogiannis 2014; Mattoo et al. 2013; Burniaux, Chateau, and Duval 2013; Li et al. 2013; Li, Wang, and Zhang 2012; Dong and Whalley 2012a; Kaufmann and Weber 2011; Lockwood and Whalley 2010; Elliott et al. 2010; Clarke 2010). Lockwood and Whalley (2010) argue that BTA is not a new issue; it arose during the climate change debate and was also a contentious issue in the 1960s when the EU was adopting the value-added tax (VAT) as a tax harmonization target.

Although a large number of studies have analyzed the impacts of BTAs, the results are divergent. For example, Dong and Whalley (2012a) and Tang et al. (2015) show that a BTA tax imposed by the rest of the world on Chinese imports would be small. On the other hand, Mattoo et al. (2013) argue that BTAs could be highly damaging to developing countries, especially China and India. Alton et al. (2014) show that a border tax imposed by the rest of the world would be more damaging to South Africa than a domestic carbon tax.

Alternative measures have been investigated in the literature to lower the competitiveness impacts of a unilateral carbon tax (Böhringer et al. 2017; Böhringer, Rosendahl, and Storrøsten 2017; Gray and Metcalf 2017; Metcalf 2014). As suggested by Metcalf (2014), these measures include (i) general cuts in payroll and corporate income taxes for EITE industries, (ii) providing corporate income tax credits tied to carbon tax payments of EITE industries, and (iii) providing disproportionate relief indirectly to EITE sectors whereby carbon tax revenue is used to lower the top corporate income tax rate. No consensus, however, exists on which compensating measure would be the best on environmental and economic grounds. The selection of the compensating measures depends on multiple factors such as the level of a unilateral carbon tax in a country, the structure of international trade of this country, levels and types of existing taxes influencing domestic production and international trade, et cetera. For example, Gray and Metcalf (2017) find that a system of carbon credits tied to carbon tax payments and output based tax credits provide better incentives to firms than allowing a deduction on the corporate income tax for carbon tax payments. Böhringer et al. (2017) finds that if the larger trading partner (here, the United States) does not have a carbon tax and the smaller partner (here, Canada) introduces one, the output-based rebate (OBR) rates needed to compensate EITE firms in Canada to stay at the level before the carbon tax would be insensitive to US carbon policies. On the other hand, the Canadian OBR rates drop by almost 50 percent if the United States also imposes an equally high carbon tax as in Canada. Böhringer, Rosendahl, and Storrøsten (2017) shows that a compensating measure that combines OBR to the production of EITE goods with a consumption tax on all users of the same EITE goods would be better than BTA, economically (welfare improving), and also politically, as BTA is contentious under existing World Trade Organization (WTO) rules.

Some of the approaches, suggested by the literature, to address BTAs would be difficult to implement in practice. Existing WTO rules do not have provisions for such adjustments. A new negotiation would be required to revise WTO rules to accommodate BTAs, which is complicated and time-consuming. BTAs are problematic for achieving the short-term targets of the Paris Climate Agreement (i.e., achieving NDCs). This is because BTAs might unfairly penalize a country meeting its Paris mitigation pledge through non-pricing policies. Instead of BTAs, exemptions for inframarginal fuel use, like in the case of a federal carbon tax backstop in Canada, could be an alternative to the output-based rebate. In fact, if a universal carbon tax with a floor price, as discussed in International Monetary Fund (2019), is introduced, the leakage and competitiveness concerns will be gone while achieving the short- and long-term objectives of the Paris Agreement.

5.5 *Setting the Carbon Tax Rate*

Economic theory suggests that an optimal carbon tax rate is one that equalizes the marginal cost of carbon abatement with the marginal damage in the absence of the abatement. Marginal damage is also referred to as the social cost of carbon (SCC) (Nordhaus 2017). Estimating the SCC is highly complex due to huge uncertainties in estimating climate change damages, and the values of SCC estimated by some existing studies vary widely (Pindyck 2017). Using the SCC approach, Nordhaus (2017) estimates a carbon tax with a rate of \$31/tCO_2 (2010 price) in 2015, increasing gradually to reach \$103/tCO_2 in 2050. The estimate is, however, sensitive to several factors—discount rate, uncertainty in the estimations of damages, besides all other uncertainties embedded in the integrated assessment model (IAM) with a 100-year time horizon. Instead of using the SCC approach, the carbon tax rate can be estimated based on international and national targets to limit GHG emissions because these targets have been set through international climate negotiations such as the Paris Climate Agreement.

Rate design depends on the purpose and scope of the carbon tax. A universal carbon tax has a different rate than a national or regional tax. The rate also depends on targeted emissions reductions and the tax base. An efficient carbon tax should be introduced to all fuels in all sectors in proportion to carbon emissions from fuel consumption. In practice, however, carbon taxes are found to be distorted because some carbon emission activities or sectors are exempted. Most of the carbon tax introduced to date in various parts of the world have some distortions. Another important issue related to the tax rate is whether the rate is kept the same for the entire time horizon considered or if it follows a step function (i.e., kept at a fixed rate for some years and increased to the next fixed rate for the next time period) or changes every year. Existing literature has shed light on this issue.

A few studies have analyzed universal carbon tax to meet a specific target for global GHG reduction, for example, meeting the target envisioned by the Paris Climate Agreement. Dietz et al. (2018) estimate the carbon tax rates under 1.5°C and 2°C scenarios. They find that the median rates of the universal carbon tax under the 1.5°C scenario would be US\$85/tCO$_2$, US\$145/tCO$_2$, and US\$4,550/tCO$_2$ (all 2005 price) in 2020, 2030, and 2100, respectively. The tax rates would be about three folds lower under the 2°C scenarios. Using simulations results from a number of IAMs, Guivarch and Rogelj (2017) show that meeting the 2°C scenario with 66 percent probability would require universal carbon tax with rates (measured in 2005 price) varying between US\$15 to 360/tCO$_{2e}$ in 2030, US\$45 to 1,000/tCO$_{2e}$ in 2050, and US\$140 to 8,300/tCO$_{2e}$ in 2100. The wide variations in the carbon tax rates have resulted from the uncertainties on drivers of GHG pathways and differences in underlying assumptions between the IAMs.

The International Monetary Fund (2019) finds that a carbon tax of US\$35/tCO$_2$ (2017 price) would be sufficient to meet the NDCs of large emitters, on average. It would reduce G-20 countries' aggregate emissions by 23 percent from the business as usual (BAU) scenario in 2030, whereas their NDCs require only 12 percent. A US\$70/tCO$_2$ carbon tax would reduce G-20 countries' aggregate emissions by 33 percent, which is consistent with the 2°C target, the long-term objective of the Paris Climate Agreement. The High-Level Commission on Carbon Prices, led by Joseph Stiglitz and Nicholas Stern, concludes that a carbon tax with the rate US\$40–80/tCO$_2$ by 2020 and US\$50–100/tCO$_2$ by 2030 would be needed to meet the 2°C or lower targets (Stigliz and Stern 2017). However, the tax rates recommended by the report are based on the commission members' judgment.[21]

There are several studies at the national level determining the carbon tax rate required to meet countries' NDCs. Timilsina, Cao, and Ho (2018) find that if China meets its NDC, which is 60–65 percent reduction of its CO$_2$ intensity of GDP from the 2005 level, it requires a carbon tax with the rates varying from ¥26/tCO$_2$ to ¥157/tCO$_2$ in 2030, depending on the design parameters of the carbon tax. If the target is 60 percent reduction of emissions intensity, a small carbon tax (¥1.6/tCO$_2$) can be introduced now, and gradually increased to ¥27/tCO$_2$ by 2030. If the target is 65 percent reduction of emissions intensity, the required

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[21] According to the report, the judgment was drawn considering technological roadmaps and assessments, national pathway analyses, and IAMs.

carbon tax now would be ¥9.8/tCO_2, allowing it to increase gradually to reach ¥157/tCO_2 in 2030. The tax rate is also sensitive, though slightly, to tax revenue recycling schemes. The 2030 tax rate to meet the 65 percent intensity reduction target would be ¥152/tCO_2 if the tax revenue is recycled to households through a lump-sum rebate instead of using it to cut the income tax rate assumed in the earlier case. Timilsina, Cao, and Ho's (2018) study also confirms, although it is intuitive, that a carbon tax with a gradually increasing rate would be more efficient (i.e., lower economic costs) than a flat or fixed tax rate to meet the target set for a future year. Similar findings are reported by Chen and Hafstead (2019) while estimating the carbon tax rate to meet the United States' pledge during the Paris Climate Agreement. Chen and Hafstead find that a carbon tax introduced in 2019 and kept at a fixed rate of \$43.40/tCO_2 would be enough to reduce US emissions 28 percent below its 2005 level in 2025 when the tax revenue is recycled to households as a lump-sum rebate. If the revenue is used to cut personal or corporate income taxes, the corresponding tax rates would be, respectively, \$43.79/tCO_2 and \$45.40/tCO_2. Chen and Hafstead also illustrate how much the tax rate alters when the duration between the carbon tax starting year and the emissions reduction target year changes. They show that if the duration decreases by two years (i.e., the carbon tax starts in 2021 instead of 2019), the tax rate increases by 9 percent, and if the duration decreases by four years (i.e., the carbon tax starts in 2023), the required tax rate increases by 23 percent.

6. *Implementation Challenges*

The carbon tax faces several challenges for its implementation. The general public has resistance or reluctance toward new taxes or increases in existing taxes. Politicians are sensitive about supporting a tax because it risks eroding their voter bases. The current energy regulatory system might be unfavorable to a carbon tax (e.g., existing fuel subsidies and fixed retail pricing for energy commodities). This section discusses these challenges, presenting as much empirical evidence as available in the literature.

6.1 *Public Perception of the Carbon Tax*

Governments or policy makers who are reluctant to introduce a carbon tax often argue that the general public does not like a carbon tax. Whether or not the general public opposes a carbon tax depends on how well the intentions and implications of the proposed carbon tax are communicated to them. Even if they oppose it initially with a perception that the carbon tax would impose a huge burden on them, their opposition may not be sustainable once they are well informed about the pros and cons of the tax. Murray and Rivers (2015) show, using polling data, that the majority of the public opposed the carbon tax when it was introduced in British Columbia for the first time in 2008. After three years of implementation, however, the public generally supported the carbon tax. Gevrek and Uyduranoglu (2015) conduct a choice experiment in Turkey to assess public preference for a carbon tax and show that Turkish people prefer a carbon tax if its design is progressive.

Baranzini and Carattini (2017) assess public acceptability of carbon taxes in Geneva, Switzerland, using survey data and find that individuals are more concerned with the environmental effectiveness of a carbon tax than its economic burden. They find that people are interested in receiving more local environmental benefits from a carbon tax. They do not worry about competitiveness issues, but express concerns about carbon tax's distributional effects. The study concludes that effective communications, particularly explaining the primary and ancillary benefits of carbon taxes, are essential for improving its acceptability. Although the findings look intuitive, it cannot be generalized because the Swiss population's level of environmental awareness is much higher than that in many developing countries.

Public communications and debates were exercised in some countries where a carbon tax was introduced. For example, although the carbon tax in Australia was withdrawn for political reasons two years after its introduction in 2012, public debate and citizens' engagement were exercised before the introduction. Then Australian Prime Minister, Julia Gillard, called for a high-profile citizens' assembly in July 2010 to gain community consensus on the proposed carbon tax (Lo et al. 2013). A lengthy public debate occurred before the introduction of carbon pricing, including a carbon tax in Canada (Harrison 2012). In South Africa, the government's assessment (through studies, consultations) and public debate on carbon taxes started a decade before its introduction in 2019. China piloted seven city-level emissions trading schemes before it finally introduced a national emissions trading scheme in November 2017. Years of public debate took place in British Columbia on selecting carbon mitigation policies, although then Provincial Premier Gordon Campbell introduced a carbon tax in 2008 (Harrison 2012).

6.2 *Economic Structure and Energy Market*

A carbon tax may not produce the desired level of emission reduction in certain economies due to the existing economic structures and markets. In economies where the transport sector is the main contributor to national GHG emissions, a carbon tax would be too expensive because the consumption of petroleum in this sector is too inelastic due to the lack of alternative transportation modes. Decarbonization of the transport sector through electric or hybrid vehicles is too expensive even if electricity is generated from zero-carbon sources (e.g., solar and wind in small island states).

A carbon tax may not be an ideal instrument to reduce GHG emissions in countries where government-owned electric utilities are the primary sources of those emissions. Instead, electric utilities should invest in low-carbon technologies. If the low-carbon technology-based electricity supply system would be expensive as compared to the status quo, the incremental cost of electricity supply will be passed to consumers by raising the electricity tariff. The increased electricity tariff encourages consumers to reduce wasteful use of electricity through energy conservation measures.

In many countries, the energy market is distorted. State-run energy supply companies (i.e., electricity and gas utilities, oil refineries, oil distribution companies) are often subsidized. The retail energy price is fixed and heavily subsidized. For example, Chile has introduced a carbon tax (US$5/t$CO_2$). The tax, however, may not pass through the retail price of electricity because the current regulation does not mandate the electricity utility to consider the carbon tax while dispatching generating plants. Moreover, the existing regulation allows side payments to reduce the economic losses of some CO_2-emitting electricity generation units (Diaz, Munoz, and Moreno 2020). Even in the United States, where competitive pricing is a norm, Ganapati, Shapiro, and Walker (2020) find that only 70 percent of energy price-driven changes in input costs get passed through to consumers. Globally, energy subsidy and its associate costs account for $5.2 trillion (2015 price) or 6.5 percent of the global GDP (Coady et al. 2019). An upstream carbon tax does not pass through the consumers unless the existing energy market is reformed. Introducing a carbon tax may not be appropriate unless existing subsidies to fossil fuels are eliminated. Energy market reforms, including the removal of fossil fuel subsidies, is a politically sensitive issue, and might take many years even if policy makers launch necessary initiatives now.

6.3 *Political Economics*

One of the biggest challenges to the introduction of a carbon tax is political economics. In some cases, the issue is ideologically aligned with the position of political parties. In Australia and Canada, carbon tax often becomes an agenda in federal and provincial elections. As already mentioned earlier in this paper, Prime Minister Julia Gillard's Labor government in Australia introduced a carbon tax in 2012. It became a contentious issue during the 2013 parliamentary election. When the Liberal Party won the election, Prime Minister Tony Abbott scrapped the carbon tax in 2014. In Canada, Prime Minister Justin Trudeau's liberal government introduced a federal carbon tax in 2018. The Conservative Party of Canada campaigned against it in the 2019 federal election. However, the Conservative Party could not win the election, and the carbon tax has continued. Similar cases were repeated in provincial elections in Canada. The National Democratic Party introduced the carbon tax in the Canadian province of Alberta in 2016, which was repealed when the Conservative Party came into power in 2019. In Ontario, Canada, a carbon pricing system (cap and trade) was introduced by the liberal government in 2017; it was abolished in 2018 when the Progressive Conservative Party came into power. In the United States, more than 50 carbon tax bills have been introduced to Congress since 1990. None of them have been successful despite the fact that some of them were bipartisan bills.[22, 23]

A political party's position on carbon pricing is often shaped by their voter base. In economies where the fossil fuel industry plays a major role in the economy (GDP and employment), politicians are sensitive toward any policy that adversely affects the industry. This is the case in Australia, a coal and gas exporting country, and Alberta, Canada, where the oil and gas industry is the backbone of the economy. This is generally true in all oil-exporting countries. Instead of broader policies like carbon pricing, these countries prefer narrow and measured nonmarket instruments (e.g., investment in renewable energy and energy efficiency improvement) that do not directly affect their fossil fuel industry, at least exports of their fossil fuels.

Another major concern that politicians have is the political flashpoint that gets triggered when existing taxes are increased or a new tax is introduced. Announcemens of fuel price increases caused violent demonstrations around the world, such as in Malaysia in 2008, Pakistan in 2009, Nigeria in 2012 and 2020, Haiti in 2017, France in 2018, and Iran, and Zimbabwe in 2019. In some cases, the demonstrations led to the fall of incumbent governments. In 2017, for example, Haiti's Prime Minister Jack Guy Lafontant resigned after days of riots sparked by the government's announcement to increase fuel prices. The price hike was suspended. In 2018, a fuel price hike triggered a violent demonstration in France, known as the "yellow vest" demonstration. The French government later suspended the price hike. Often, a demonstration might result from compounded grievances due to many concerns people had, such as increasing the cost of living and social and fiscal inequalities, then an announcement of a fuel price hike, but the latter sparks it. It provides an easy opportunity for opposition parties to put pressure on incumbent governments. Since the carbon tax is a fuel tax, it poses a political risk, particularly when

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[22] Price on Carbon. "Know the Legislation." https://priceoncarbon.org/business-society/history-of-federal-legislation-2/.

[23] In the 116th Congress more recently, eight carbontax-related bills have been introduced, four of them are bipartisan.

it is introduced without proper communications to the general public.

6.4 *Other GHG Emissions*

One key drawback of a carbon tax is that its application is difficult in controlling non-CO_2 GHGs, which accounts for about 30 percent of global GHG emissions (Olivier and Peters 2020). This is because the sources of other GHG are heterogeneous, and their global warming potentials are much different from that of CO_2. These characteristics of non-CO_2 GHGs make it difficult to find a carbon tax base. For CO_2, finding a tax base is convenient; it is the carbon contents of fossil fuels, and CO_2 emissions are directly linked to carbon contents with some exceptions. For non-CO_2 GHGs, several factors influence their emissions from a source. For example, emission of methane, a non-CO_2 GHG, depends on the type and quality of lands, use of fertilizers for agriculture, and livestock feeding practices. Nevertheless, a few studies have attempted to capture some of these emissions, particularly those from land-use change, forestry, and agriculture under a carbon tax (Gurgel and Paltsev 2014; Gurgel, Reilly, and Blanc 2021). They express these GHG emissions as a function of outputs from the corresponding sector, such as non-CO_2 GHG emissions as a function of the gross output from the agriculture or forestry sectors.

The control of non-CO_2 GHGs is critical in countries like Brazil, Indonesia, and the Democratic Republic of Congo, where the forestry sector is the major contributor to national GHG inventories. In Brazil, most of the emissions reductions required to achieve its NDCs are expected from reducing deforestation, reforesting degraded land areas, intensifying agricultural and livestock production, renewable energy, and energy efficiency improvement. Gurgel, Reilly, and Blanc (2021) analyze the impacts of meeting Brazil's NDCs, in which the country pledged to reduce its GHG emissions below the 2005 level by 37 percent by 2025 and 43 percent by 2030. They find that the required carbon tax to meet Brazil's NDC in 2030 would be small, US\$3/tCO_2, because emissions reductions from the forestry and agricultural sectors are cheaper.

7. *Knowledge Gap*

Although a large number of studies have been carried out covering many issues related to carbon taxes over the last 30 years, a knowledge gap still exists in some specific areas. Below, I highlight some of them.

Efficiency versus equity of revenue recycling schemes. A general conclusion drawn from the literature is that using carbon tax revenue for cutting existing distortionary taxes, particularly personal and corporate income taxes, is more efficient economically (i.e., GDP/welfare gain or smaller GDP/welfare loss) than transferring it to households through a lump-sum rebate. On the other hand, the lump-sum rebate helps make a carbon tax progressive, as it helps low-income households receive higher welfare compared to high-income households. Thus, lump-sum transfer appears to be a pro-poor revenue recycling scheme, and it would be better from an equity perspective. Moreover, use of carbon tax revenue to promote clean energy technologies or to finance energy-efficient appliances would be preferable, from an environmental perspective, as such a scheme brings double environmental benefits (i.e., reductions of emissions due to the carbon tax and further reduction of emissions from the implementation of clean and energy-efficient technologies). This scheme is, however, economically inefficient. A question arises whether it would be preferable to select a revenue recycling scheme that distributes the carbon tax revenue for various purposes, say a part of the revenue to transfer to poor households (instead of all households), a part for cutting existing distortionary taxes, a part for subsidizing clean energy. Studies investigating a portfolio of revenue recycling schemes are lacking. Since countries vary in terms of their economic structures and social needs, a study carried out for a country cannot be generalized. Thus, country-specific studies on this topic are warranted.

Carbon tax and poverty alleviation. One critical question missing from the carbon tax literature is how does the carbon tax influence poverty? Considering a carbon tax's potential disproportionate impacts on low-income households' welfare, one could expect that a carbon tax might exacerbate poverty. On the other hand, if carbon tax revenue is recycled to households below extreme poverty, it could significantly contribute to eliminating extreme poverty. However, no research has been done in this area.

Costs of sector and fuel exemption of carbon taxes. Studies that analyze key issues related to a carbon tax in practice are also missing. For example, sectoral exemption (i.e., not to impose a carbon tax on certain fuels or sectors) is a common practice. A carbon tax with no sectoral or fuel exemption would be less costly than that with the exemption for a given level of emissions reduction. This is an established theory. However, the practice of exemption will continue for political reasons. It is, therefore, important to quantify the costs of exemptions and communicate them to policy makers. Moreover, these costs would be different across the economies, depending on their economic and international trade structures. It is imperative to assess the costs of sectoral and fuel exemptions of a carbon tax across economies. The results would help policy makers to decide whether or not to adopt an exemption to a carbon tax for a sector or fuel.

Analysis of carbon taxes on a full social cost basis. A common limitation of most studies assessing the cost of a carbon tax is the ignorance of costs other than pure economic costs. First, only limited studies have accounted for the benefits of climate change mitigation.[24] Understandably, quantifying climate change benefits is complicated due to the scale of uncertainties. However, this excuse results in incomplete information on the cost of a carbon tax. Recently, some studies (e.g., Li et al. 2018, Parry et al. 2015a, Parry et al. 2014, Parry et al. 2012a) have measured and highlighted the local environmental benefits of a carbon tax. If both climate change mitigation benefits and the local environmental benefits are accounted for, a carbon tax could generate overall net social benefits. However, knowledge in this area is highly limited. More studies are needed. Rigorous analyses and effective communication of the results could significantly enhance the carbon tax policy's political and public acceptance.

Overlap with other climate policies. In many countries, including EU member states, several policy instruments for climate change mitigation (e.g., carbon tax, emission trading, renewable energy mandates, building energy efficiency standards, vehicle mileage standards) have implemented simultaneously. Theoretically, other climate policies may not be needed when a carbon tax is in place; a carbon tax is supposed to trigger GHG mitigation activities intended by other policy instruments. For example, if an adequate level of a carbon tax is introduced, clean and renewable energy would be more competitive with fossil fuels, and the market will implement clean and renewable energy sources. When multiple policies are introduced, some sectors get

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[24] It is understandable why climate change benefits are ignored when an analysis is carried out for a single country, especially a small developing country whose contribution to global GHG emissions is small.

overburdened due to the overlapping of policies. A key question here is, what is the most efficient option to avoid such overlapping? How would different policies be mixed, if needed, so that the portfolio of policies leads to optimal GHG mitigation with minimum social costs? Studies answering these questions are rare in the existing literature.

8. *Conclusions*

The carbon tax is an economically efficient instrument for combating climate change, one of the greatest threats to human civilization. Different types of policy instruments, such as public investment in low carbon infrastructure, regulatory measures such as renewable energy mandates, and pricing instruments, such as carbon taxes and cap and trade, are being used to reduce GHG emissions. Compared to public investment and regulatory instruments, a carbon tax can have a broader base. It provides incentives to all stakeholders, including producers, consumers, and governments. Despite these merits, carbon taxes face challenges for political and, to some extent, social acceptability. Governments are not enthusiastic about their implementation because they raise energy prices, which is politically and socially sensitive and could trigger violent demonstrations, such as the yellow vest movement in France. Although the carbon tax has been introduced in some economies, it is distorted. The tax rate is far lower than its optimal level. In some cases, key emitters are exempted. In this context, this review article attempts to synthesize the academic literature and shed light on various issues related to the carbon tax.

Early studies examining the macroeconomic impacts of the carbon tax concluded that carbon taxes cause overall economic loss measured in terms of GDP or welfare if the climate change benefits and other environmental co-benefits are ignored. More recent studies, however, contradict those findings. They show that the direction and magnitude of the macroeconomic impacts of a carbon tax depend on its design architecture, particularly the selection of revenue recycling schemes. Recent econometric analyses investigating the effects of existing carbon taxes do not find a negative relationship between the carbon tax and key macroeconomic variables—GDP and employment. If environmental and fiscal co-benefits are taken into account, a carbon tax does not cause welfare loss. In some cases, such as China, a carbon tax can be justified based on the local environmental (or health) benefits alone. These findings could be useful to clarify the presumption that carbon tax is economically harmful.

Literature also provides clear guidance on selecting the schemes to recycle carbon tax revenues to the economy. Not recycling carbon tax revenue (i.e., using it for government administrative expenses) causes the highest welfare or economic cost. Recycling the revenues to households through a lump-sum transfer would be better than the no-recycling case in terms of economic impacts. It would be better further (lower reduction of welfare or economic output) if carbon tax revenues are recycled to cut existing distortionary taxes (e.g., personal income tax cut, labor tax cuts). Recycling the tax revenue to boost economic outputs through investments or corporate or capital tax cuts could increase welfare and GDP. Using carbon tax revenues for subsidizing clean and renewable energy technologies is appealing from the environmental perspective because it reduces emissions further. However, it reduces welfare and GDP unless the environmental benefits are taken into account.

The efficiency and equity aspects of the carbon tax are the most contentious issues, as they often counteract and create a dilemma to policy makers. A carbon tax with the preferable revenue recycling scheme on efficiency grounds (e.g., recycling carbon tax revenue to cut the capital tax) would tend to be regressive from an equity perspective. This is because it tends to benefit high-income households more than low-income ones. On the other hand, a carbon tax with a less preferable revenue recycling scheme from an efficiency perspective (e.g., lump-sum transfer of carbon tax revenues to households) would be superior from an equity perspective, as it is progressive on distributional grounds. This finding suggests that policy makers should take both equity and efficiency attributes into account while designing a carbon tax system.

In the case of a unilateral carbon tax, the loss of competitiveness of EITE sectors is of great concern; it exacerbates the resistance to a carbon tax. The literature proposes several options for border tax adjustments to address this concern. These include cutting payroll and corporate income taxes in EITE industries, providing an output-based rebate to EITE sectors using carbon tax revenues. However, no consensus occurs in the literature to rank the merits of these compensating measures. The selection of compensating measures depends on multiple factors, such as the level of a unilateral carbon tax in a country, its structure of international trade, the level and types of existing taxes influencing domestic production and international trade, etc. The border tax adjustment is, however, politically contentious.

The existing literature sheds light on designing a carbon tax architecture. A universal carbon tax with a floor rate—the minimum rate applied in all countries allowing the individual countries to have a higher rate based on their GHG mitigation targets—would be the better approach instead of unilateral carbon taxes in some countries. Some countries would prefer to have a higher rate, which could help them not only efficiently meet their pledges under the Paris Agreement, but also reduce their harmful local environmental pollution. A universal carbon tax avoids the concern of competitiveness and the need for the border tax adjustment. The design architecture should address the distributional issue through the selection of appropriate revenue recycling schemes to make it politically and socially acceptable. The extensive pool of knowledge generated by rigorous research over the last three decades could be instrumental in designing a new and effective carbon tax system and reforming the existing carbon taxes in practice.

Appendix

TABLE A1
CLASSIFICATION AND EVOLUTION OF CARBON TAX LITERATURE

Typology (Issues focused on)	Studies published in years				
	1995 and Before	1996–2000	2001–10	2011–15	After 2015
Assessment of economic costs of the carbon tax (mostly general equilibrium effects)	Kaufmann (1991)—world; Herber and Raga (1995)—European Union; Goulder (1995b)—United States; Jayadevappa and Chhatre (1995)—India; Proost and van Regemorter (1992)—Belgium; Pezzey (1992)—European Union; Bossier and De Rous (1992)—Belgium; Agostini et al. (1992)—Europe	Bovenberg and Goulder (1997)—United States; Parry (1997)—United States; Zhang (1998)—China; Goulder (1998)—United States; Fisher-Vanden (1997)—India; Bovenberg and Goulder (1996)—United States	Bagnoli et al. (2008)—Russia; Wissema and Dellink (2007)—Ireland; Matsumoto and Fukuda (2006)—global; Timilsina and Shrestha (2002)—Thailand	Cabalu et al. (2015)—Philippines; Nekrasenko et al. (2015)—Ukraine; Gurgel and Paltsev (2014)—Brazil; Allan et al. (2014)—Scotland; Espinosa and Fornero (2014)—Chile; Mahmood and Marpaung (2014)—Pakistan; Meng et al. (2013)—Australia; Conefrey et al. (2013)—Ireland; Devarajan et al. (2011)—South Africa	Adetutu et al. (2020)—United Kingdom; Zhang et al. (2019)—China; Andersson (2019)—Sweden; Zhu et al. (2018) and Parry and Mylonas (2017)—Canada; Jorgenson et al. (2018)—United States; Lee et al. (2018)—Japan; Pradhan et al. (2017)—India; Liu et al. (2017)—Guangdong, China; Timilsina et al. (2018), Dong et al. (2018), and Zhang et al. (2016)—China; Dissanayake et al. (2018)—Pakistan and Sri Lanka; Nurdianto and Resosudarmo (2016)—ASEAN; van Heerden et al. (2016)—South Africa; Benavente (2016)—Chile; Pereira et al. (2016)—Portugal; Calderon et al. (2016)—Colombia; Rivera et al. (2016)—Mexico
Distributional impacts across household income groups	Hamilton and Cameron (1994)—Canada		Feng et al. (2010)—United Kingdom; Callan et al. (2009)—Ireland; Hassett et al. (2009)—United States; Verde and Tol (2009)—Ireland; Fullerton and Heutel (2007)—Japan; Brenner et al. (2007)—China	Rausch and Reilly (2015)—United States; Williams et al. (2014)—United States	Fremstad and Paul (2019)—United States; Renner (2018)—Mexico; Farrell (2017)—Ireland; Rosas-Flores (2017)—Mexico; Rezai and Van der Ploeg (2016)—world; Beck et al. (2016)—British Columbia, Canada; Caillavet et al. (2019)—France
Tax revenue and recycling schemes	Parry (1995)—United States; Jaeger (1995)—global; Goulder (1995a)	Goulder et al. (1997)—United States; Parry et al. (1999)—United States; Parry and Bento (2000)—United States; McKitrick (1997)—Canada; Welsch (1996)—Germany	Galinato and Yoder (2010)—United States; Lu et al. (2010)—China; Bento et al. (2009)—United States; Kiuila and Markandya (2009)—Estonia; Timilsina and Shrestha (2007)—Thailand; Metcalf (2007)—United States; Parry (2003); Goodstein (2003)—world.	Jorgenson et al. (2015)—United States; McKibbin et al. (2015)—United States; Rausch and Reilly (2015)—United States; Tuladhar et al. (2015)—United States; Beck et al. (2015)—British Columbia; Williams et al. (2014)—United States; Orlov and Grethe (2014)—Russia; Timilsina et al. (2011)—world; Kallbekken et al. (2011)—experimental work	Carl and Fedor (2016)—world; Rivera et al. (2016)—Mexico; Verde et al. (2016)—European Union

(Continued)

TABLE A1
Classification and Evolution of Carbon Tax Literature *(Continued)*

Typology (Issues focused on)	Studies published in years				
	1995 and Before	1996–2000	2001–10	2011–15	After 2015
Competitiveness and border tax adjustment (BTA)			Cloete and Robb (2010)—South Africa; Lockwood and Whalley (2010)—global; Elliott et al. (2010)—global; Clark (2011)—global	Tang et al. (2015)—China; Eichner and Pethig (2015); Keen and Kotsogiannis (2014); McLure (2014); Elliott and Fullerton (2014); Mattoo et al. (2013)—world; Burniaux et al. (2013)—world; Li et al. (2013)—China; Li and Zhang (2012)—China; Dong and Whalley (2012a); Dong and Whalley, (2012b); Fischer and Fox (2012); Moore (2011); Kaufmann and Weber (2011)	Aldy (2017a)—United States; Trachtman (2017)—United States; Gray and Metcalf (2017)—United States; Siriwardana et al. (2017)—Australia; Böhringer et al. (2017)—United States and Canada; Böhringer, Rosendahl, and Storrøsten 2017—world; Kortum and Weisbach (2017)
Reviews and qualitative analysis	Oates (1995); Poterba (1993); Hoeller and Coppel (1992)		Aldy et al. (2010); Metcalf (2009b); Ekins and Baker (2001)	Jenkins (2014)—world; Tietenberg (2013)—world; Elgie and McClay (2013)—Canada; Parry et al. (2012a)—world; Aldy and Stavins (2012a)—world; Clarke (2011)—Australia; Parry et al. (2012b)—global	Aldy et al. (2017); Hafstead et al. (2017); Aldy (2017b); Murray et al. (2017)
Carbon tax versus other policies	Weitzmann (1974)		Timilsina (2009); Metcalf (2009a); Aldy et al. (2008); Grimaud and Lafforgue (2008); Green (2008); Gerlagh and van der Zwaan (2006); Kim et al. (2004); Böhringer et al. (2003); Parry (2003); Newell and Pizer 2003; Hoel and Karp 2002	Zakeri et al. (2015); Goulder and Schein (2013); Wirl (2012); Levin et al. (2011); Murphy and Jaccard (2011); McKibbin (2011)	Davis and Knittel (2019); Fried (2018)
Sectoral studies	Newbery (1992)—electricity		Guthrie and Kumareswaran (2009)—forestry; Shrestha et al. (2008)—electricity; Tol (2007); Floros and Vlachou (2005)—manufacturing; Schneider and McCarl (2005)—agriculture; Schunk and Hannon (2004)—agriculture; Simshauser and Docwra (2004)—electricity	Raux et al. (2015)—transport; Rivers and Schaufele (2015)—transport; Klier and Linn (2015)—transport; McKibbin (2014)—electricity; Li et al (2014)—electricity; Martin et al. (2014)—manufacturing; Keen et al. (2013)—transport; Choe (2013)—transport; Chernenko (2013)—electricity; Caurla et al. (2013)—forestry; Di Cosmo et al. (2013)—energy; Barua et al. (2012)—forestry	Gupta et al. (2019)—transport; Tsai et al. (2017)—building; Ntombela et al. (2019)—food; Qiu et al. (2020) – air transport

(Continued)

TABLE A1
Classification and Evolution of Carbon Tax Literature *(Continued)*

Typology (Issues focused on)	Studies published in years				
	1995 and Before	1996–2000	2001–10	2011–15	After 2015
Perception of a carbon tax			Bristow et al. (2010)—global	Murray and Rivers (2015)—Canada; Gevrek and Uyduranoglu (2015)—Turkey; Bumpus (2015)—British Columbia, Canada; Lo et al. (2013)—Australia	McLaughlin et al. (2019)—Scotland; Baranzini and Carattini (2017), Carattini et al. (2017)—Switzerland
Specific issues	Wirl (1995)—carbon tax and fossil fuel exploitation; Ulph and Ulph (1994)—optimal path of carbon tax; Lund (1994)—carbon tax and R&D; Golombek and Braten (1994)—optimal carbon tax; Wirl (1994)—consumer and producer interactions; Hoel (1993a)—harmonization of carbon tax; Hoel (1993b)—intertemporal properties of carbon tax; Sinclair (1992)—carbon tax path; Hoel (1992)—domestic versus international carbon tax	Böhringer et al. (1997)—sectoral exemption; Farzin and Tahvonen (1996)—optimal path for carbon tax; Lewis and Seidman (1996)—carbon tax and optimal growth; Ekins (1996)—carbon tax and secondary benefits; Hoel (1996)—sectoral differentiation of carbon tax rate	Golombek et al. (2010)—carbon tax and innovation; Gerlagh et al. (2009)—optimal carbon tax and innovation; Baker and Shittu (2006)—carbon tax and R&D; Li (2006)—health benefits of carbon tax in Thailand; Gerlagh and Lise (2005)—carbon tax and technological change; Liski and Tahvonen (2004)—carbon tax and OPEC rent; Bye and Nyborg (2003)—sectoral differentiation of carbon tax rate; Jaeger (2002)—carbon tax and productivity	Choi (2015)—impacts of carbon tax on voluntary offsets; Meng (2015)—sectoral exemption under carbon tax; Pillay and Buys (2015)—carbon tax and corporate governance; Parry et al. (2015a)—co-benefits of carbon tax; McAusland and Najjar (2015)—carbon footprint taxes; Parry et al. (2014)—optimal carbon tax rates across countries; Dullieux et al. (2011)—carbon tax and OPEC rent; Edenhofer and Kalkuhl (2011)—green paradox; Dong and Whalley (2012b)—Carbon tax and OPEC monopoly rent; Strand (2013)—carbon tax and offsets; Maruyama (2011)—carbon tax, ETS and WTO; Hammar and Sjostrom (2011)—behavior impacts on carbon tax rate increase	Yamazaki (2017)—carbon tax and jobs in British Columbia, Canada; Jakob et al. (2016)—carbon tax revenue for global infrastructure financing; Aghion et al. (2016)—carbon tax and technological change in auto industry; d'Autume et al. (2016)—sectoral differentiation of carbon tax rate; van der Ploeg, and de Zeeuw (2016)—carbon tax, green paradox and leakage
Analyzing the Paris Climate Agreement	Long-term objective (meeting 2° Celsius or lower targets in the long run)				Dietz et al. (2018); Stigliz and Stern (2017)
	Short-term objective (meeting the nationally determined contributions)				Lee et al. (2018)—Japan; Pradhan et al. (2020)—Nepal; Wattanakuljarus (2019) –Thailand; IMF (2019)—world; Chen and Hafstead (2019)—United States; Timilsina et al. (2018)—China; Stigliz and Stern (2017)—world; Gurgel et al. (2017)—Brazil

TABLE A2
Classification of Carbon Tax Literature by Analytical Methodology

Main category	Subcategory	Study
Theoretical analysis		Weitzman (2014); van der Ploeg and Withagen (2014); Keen and Kotsogiannis (2014); Baylis et al (2013); Strand (2013); Dullieux et al. (2011); Golombek et al. (2010); Gerlagh et al. (2009); Wirl (2007); Baker and Shittu (2006); Liski and Tahvonen (2004); Hoel (1992, 1993a, 1993b); Sinclear (1992); Newbery (1992); Lund (1994); Golombek and Braten (1994); Wirl and Dockner (1995); Hoel (1996); Farzin and Tahvonen (1996); Kaufmann (1991)
Game-theoretic approach		Zhang and Zhu (2017); Karp et al. (2016); van der Ploeg and de Zeeuw (2016); Eichner and Pethig (2016); Wirl (2012); Wirl (1994, 1995)
Partial equilibrium analysis		Davis and Knittel (2019); Caillavet et al. (2019; Calderon et al. (2016); Pahle et al. (2013); Caurla et al (2013); Keen et al. (2013); Conefrey et al. (2013); Chi et al. (2012); Mori (2012); Murphy and Jaccard (2011); Feng et al. (2010); Guthrie and Kumareswaran (2009); Green (2008); Tol (2007); Gerlagh and van der Zwaan (2006); Gerlagh and Lise (2005); Schneider and McCarl (2005); Schunk and Hannon (2004); Li and Higano (2004); Jaeger (2002); Yokoyama et al. (2000); Cornwell and Creedy (1997); Ekins (1996); Rosendahl (1996); Jaeger (1995); Symons et al. (1994); Agostini et al. (1992); Ingham et al. (1991)
Energy sector optimization		Liu et al. (2017); Levin et al. (2011); Shrestha et al. (2008); Simshauser and Docwra (2004)
Input-output modeling		Fremstad and Paul (2019); Jiang and Shao (2014); Sun and Ueta (2011) and Wang et al. (2011); Bordigoni et al. (2012); Callan et al. (2009); Verde et al. (2009); Metcalf (2007); Bossier and de Rous (1992); Jayadevappa and Chhatre (1995); Moon (1996)
General equilibrium modeling	Single country static model	Benavente (2016); Coxhead et al. (2014); Dissou and Siddiqui (2014); Meng (2013, 2014, 2015); Devarajan et al. (2011); Timilsina (2009); Timilsina and Shrestha (2007); Timilsina and Shrestha (2002); Miyata et al. (2013); Kiuila and Markandya (2009); Wissema and Dellink (2007); Bohringer et al. (2003); Kamat et al. (1999); Bohringer and Rutherford (1997); McKitrick (1997)
	Single country recursive dynamic	Pradhan et al. (2017); van Heerden et al. (2016); Pereira et al. (2016); Cabalu et al. (2015); Mahmood and Marpaung (2014); Li et al. (2014); Liang and Wei (2012); Lu et al. (2010); Zhang (1998); Li (2006); Kim et al. (2004); Fisher-Vanden (1997)
	Single country intertemporal	Jorgenson et al. (2015); Williams et al. (2014); Goulder et al. (1997); Goulder (1998); Bovenberg and Goulder (1996); Parry (1997); Bovenberg and Goulder (1997); Parry et al. (1999); Parry and Bento (2000)
	Multi-country/region static model	Zhang et al. (2016); Nurdianto and Resosudarmo (2016); Zhou et al. (2013); Dong and Whalley (2012a,b)
	Multi-country/region recursive dynamic	Lee et al. (2018); Rausch and Reilly (2015); Allan et al. (2014); Proost and van Regemorter (1992)
	Multi-country/region intertemporal	Tuladhar et al. (2015); Welsch (1996)
	Global static	Li et al. (2014, 2013); Orlov and Grethe (2014); Burniaux et al. (2013); Mattoo et al. (2013); Fischer and Fox (2012)
	Global recursive dynamic	Gurgel et al. (2019); Rivera et al. (2016); Elliott and Fullerton (2014); Gurgel and Paltsev (2014); Dellink et al. (2013); Timilsina et al. (2011); Elliott et al. (2010)
	Global intertemporal	McKibbin et al. (2015, 2011) used for United States; Davies et al. (2014) for global; Nordhaus (2014); Pizer (2002); Roughgarden and Schneider (2002); Lewis and Seidman (1996); Pezzey (1992)
	Dynamic stochastic	Espinosa and Fornero (2014)

(Continued)

TABLE A2

Classification of Carbon Tax Literature by Analytical Methodology (*Continued*)

Main category	Subcategory	Study
Qualitative analysis		Aldy (2017); Murray et al. (2017); Jenkins (2014); Goulder, and Schein (2013); Tietenberg (2013); Elgie and McClay (2013); Rhodes and Jaccard (2013); Parry et al. (2012); Aldy and Stavins (2012); Clarke (2011); Ottmar and Kalkuhl (2011); Kaufmann and Weber (2011); Aldy et al. (2010); Clarke (2010); Metcalf and Weisbach (2009); Whitesell (2007); Matsumoto and Fukuda (2006); Ekins and Baker (2001); Oates (1995); Poterba (1991; 1993); Pearce (1991)
Econometric approach		Metcalf and Stock (2020); Adetutu et al. (2020); Ganapati et al. (2020); McLaughlin et al. (2019); Andersson (2019); Bumpus (2015); Pillay and Buys (2015); Lo et al. (2013); Di Cosmo and Hyland (2013); Bureau (2011); Lin and Li (2011); Bristow et al. (2010); Brannlund and Nordstrom (2004); Mabey and Nixon (1997)

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