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Where Is the Carbon Tax after Thirty Years of Research?

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Abstract

This paper takes a dive into the deep literature on the carbon tax accumulated through active and continuous research over the past 30 years. It also presents the ongoing debate and implementation of the carbon tax in practice. The paper discusses the evolution of the carbon tax literature, classifying it by the issues investigated and methodology used for the investigation. It finds that the literature enlightens four key issues: (i) economic impacts, (ii) choices for revenue recycling, (iii) distributional implications, and (iv) competitiveness and border tax adjustment. Quantitative analysis, especially computable general equilibrium modeling, is the main method employed in the literature. The study shows that potential adverse economic impacts and competitiveness concerns are the main impediments to the introduction of the carbon tax. Extensive examinations of carbon tax issues at the global, regional, and country levels have led to innovative measures to address these concerns. While the carbon tax was mainly a subject of academic discussion until few years back, it has generated good attention for policy makers, particularly after the Paris Agreement on climate change, and is being considered as one of the main market instruments to address global climate change. Although several important issues related to the carbon tax have been well researched, its potential interactions with poverty and shared prosperity are yet to be investigated.

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Where Is the Carbon Tax after Thirty Years of Research?[1]

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Where Is the Carbon Tax after Thirty Years of Research?

1. Introduction

Like other environmental taxes, the principle of carbon tax is based on English economist Arthur Cecil Pigou's work on welfare economics (Pigou, 1920) which 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 to society. The private costs of economic activities that cause greenhouse gas (GHG) emissions are distorted because of exclusion of costs of climate change damages. A carbon tax corrects the market distortions by taxing the carbon emissions and thereby causing emitters to pay for the social costs. Taxes on environmental externalities, including carbon tax, are referred to as Pigouvian taxes, recognizing Pigou's pioneering work on pricing of environmental externalities.[3]

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 carbon tax and other carbon pricing instruments, such as the cap and trade scheme. Since the early1990s carbon tax has attracted the attention of researchers and, to some extent, policy makers. A few countries, particularly, Scandinavian countries, introduced carbon tax in the early 1990s. Since then, academic research on carbon tax has increased rapidly and hundreds of articles have been published in peer reviewed journals addressing various issues related to carbon pricing, theoretically as well as empirically over the last 30 years.

A carbon tax has been or can be implemented in many forms. For example, a carbon tax can be imposed on fossil fuels in proportionate to CO_2 emissions released when the fuel is burned for intermediate or final consumption. This approach penalizes more a fuel with higher

[3] Economist N. Gregory Mankiw created a club to advocate carbon tax, a Pigovian tax, to mitigate climate change. Several eminent economists, scientists, journalists, lawyers, musicians, business leaders, civic society leaders and politicians have joined the 'Pigou Club' (https://gregmankiw.blogspot.com/2006/10/pigou-club-manifesto.html).

carbon contents, such as coal, petroleum coke as compared to fuels with lower carbon content, such as natural gas. Carbon tax can also be imposed on a good or service in proportionate to CO_2 emission released during its production of the good or service. While both forms of carbon tax have the same purpose – putting a price on CO_2 emission, they have different implications in terms of a carbon tax design and their effects to an economy.

The objective of this paper is to communicate to a wider audience, particularly policy makers, the most relevant knowledge produced on key issues of carbon tax over the last 30 years by peer reviewed academic research. To achieve this objective, this paper has extracted as much knowledge as possible on the most relevant contemporary topics of carbon tax from the extensive body of literature which are validated through a peer-reviewing processes and made available for global public consumption. We tried to review all studies on carbon tax published in peer reviewed journals since 1970.[4] Several databases that help retrieve literature, such as JSTOR, ECONLIT, Google Scholar, are used to retrieve the journal articles. Key words used for the literature search are "carbon tax" and "carbon pricing". Since 'carbon pricing' also includes literature related to tradable CO_2 permits or CO_2 cap and trade, we have not included that literature. And the study did not include the literature on shadow carbon price, which refers to implied per unit cost of GHG mitigation (US\$/tCO_2) to meet a specified target for GHG mitigation. While a wide range of academic journals have published research on carbon tax, the most common are, in alphabetical order: American Economic Review, Applied Energy, Canadian Public Policy, Climate Change Economics, Climate Policy, Ecological Economics, Economic Modelling, Energy Economics, Economics of Energy and Environmental Policy, Energy Policy, Environmental Economics and Policy Studies, Environmental and Resource Economics, European Economic Review, Journal of Economic Literature, Journal of Economic Perspective, Journal of Energy and Development, Journal of Environmental Economics and Management, Journal of International Economics, Journal of Political Economy, Journal of Public Economics, Journal of the Association of Environmental and Resource Economists, Land Economics, National Tax Journal, Oxford Economic Papers, Resource and Energy Economics, Review of Environmental Economics and Policy, The Energy Journal, The Scandinavian Journal

[4] We considered only the journal articles in this review. There exists some books or edited volume discussing carbon tax issues (e.g., Parry et al. 2015, Quiggin et al. 2014, Hsu, 2011). However, we do not separately discuss the books and edited volumes as they cover the similar issues discussed in journal articles included in this article for qualitative analysis of carbon tax.

of Economics and World Development. We then classified the literature based on the issues they analyzed, such economic impacts of carbon tax, schemes to recycle carbon tax revenue, distributional analysis of carbon tax, competitiveness and border tax adjustment, etc. Studies are also classified based on the analytical methodology used, such as theoretical analysis, qualitative analysis or reviews and empirical or numerical analysis. The empirical literature is further divided into various types based on the empirical techniques employed, such as computable general equilibrium modeling, input-output modeling, partial equilibrium modeling, system optimization, etc. Since the knowledge on carbon tax has been accumulated over the last 30 years of active and continuous research on various topics at global, regional and national levels, the body of literature is quite extensive. We have included in this paper only the studies published in peer reviewed journals. It is also possible that carbon tax has been examined but results are not published in peer-reviewed journals in many countries. Since 'peer-reviewed journal publication'[5] is the cut-off criteria we employed for this paper, we could not include here studies published outside the academic journals even if they might have a good quality.

A few studies (e.g., Poterba 1993; Baranzini et al. 2000; Ekins and Barker, 2001; Aldy et al. 2010; Tietenberg, 2013; Aldy and Stavins, 2012; Marron and Toder, 2014) discuss various issues related to carbon tax based on existing literature. Analyzing global warming policies from the public finance perspective, Poterba (1993) discusses basic characteristics of a carbon tax including its regressive nature, its international incidence and implementation issues. However, since most studies on carbon tax have been carried out after the publication of this study, it does not capture important findings of those studies. Baranzini et al. (2000) discusses some key features of carbon tax such as its competitiveness and distributional impacts. The arguments presented in this paper are either opinion based or based on limited studies carried out by then. Most analysis on carbon tax's competitiveness and distributional impacts are carried out after the publication of this study. 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 carbon tax, such as

[5] For this type of analysis, credible and rigid criteria are needed to decide what to include in the review because it would not be feasible to include everything available. The selection of 'peer reviewed journal publication' as the main criteria also avoids the author's subjective judgement regarding the inclusion of existing literature.

revenue recycling and double dividend arguments. As mentioned above, this study too does not capture many empirical insights brought by the studies carried out after its publication.

More recent reviews of carbon tax literature are Aldy et al. (2010), Tietenberg (2013) and Marron and Toder (2014) discuss a wide rage issues related to climate change mitigation policies, such as the integrated assessment models for climate change policy modeling, carbon pricing, marginal damage assessment or social costs of carbon. Aldy et. al. (2010) briefly discuss some issues related to carbon tax, particularly the fiscal linkages, distributional considerations, technological diffusion. However, having a much broader scope to cover many issues related to climate change mitigation, the discussions specific to carbon tax are light, as they include the knowledge provided by a few selected studies. Tietenberg (2013) offers a brief exposure of various issues related to carbon pricing including 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 and revenue recycling schemes. They do not discuss other issues related to carbon taxation.

This paper adds value to existing carbon tax literature on multiple dimensions. First, it dives much deeper into the issues specifically focusing on carbon tax instead of covering broader issues of carbon pricing or climate change mitigation policies considered in the existing review studies. Second, instead of picking a few selected studies as practiced in the existing reviews, our review attempts to cover most carbon tax literature over the last 30 years. Third, it comprehensively presents the evolution of carbon tax literature over the last 30 years, none of the existing reviews have done so. Fourth, it also classifies the existing carbon tax literature based on the analytical methodology used. Fifth, it elaborates the key message coming from the pool of academic research that would help lower the political resistance to carbon tax if communicated effectively. Sixth, it captures insights form the more recent literature not covered in the existing reviews, and finally it highlights key knowledge gaps in the field of carbon tax so that future research can be focused to contribute to filling these gaps.

This paper is organized as follows. Section 2 presents a brief review of literature by highlighting the evolution of the literature over time based on issues investigated and methodologies used for the investigations. This is followed by discussing factors that might have caused resistance to the introduction of carbon tax in Section 3. Section 4 describes how political appetite for carbon tax can be increased, followed by a detailed account of carbon tax introduced in practice by various countries or economies around the world in Section 5. Section 6 points out the research gaps in carbon tax issues. Finally, key conclusions are drawn in Section 7.

2. Carbon Tax Literature

This section highlights two important aspects of carbon tax literature. First, it discusses the evolution of carbon tax literature over time since the early 1990s by dividing the literature into different groups based on the issues addressed (Table 1). Second, it differentiates the existing studies with various methodologies used for analysis (Table 2). An in-depth discussion of hundreds of journal articles evaluating their strengths and weaknesses is beyond the scope of this paper. Our objective is to discuss (Section 3 onwards) key carbon tax issues based on evidence provided by existing studies. This section briefly elaborates information provided in Tables 1 and 2.

2.1 Typology and Evolution of the Carbon Tax Literature

Based on key issues of carbon tax analyzed over the last 30 years, carbon tax literature can be classified broadly into eight groups: (i) literature assessing the economic impacts of carbon tax in general, such as general equilibrium effects; (ii) literature investigating the distributional effects (i.e., carbon tax effects by household income groups); (iii) literature examining various schemes to recycle carbon tax revenues to the economy; (iv) literature assessing the competitiveness and emission leakage of unilateral carbon taxes and measures to mitigate these impacts; (v) literature comparing carbon tax with other policies; (vi) literature offering review and qualitative analysis of various issues related to the carbon tax policy; (vii) literature investigating impacts of a carbon tax focusing on a particular sector or activity and (viii) literature dealing with specific issues related to carbon tax. Table 1 lists key literature published in different time intervals over the last 30 years classifying them into these categories.

Table 1. Classification of carbon tax literature

Typology (Issues focused on)	Studies published in years				
	Before 1995	**1996-2000**	**2001-2010**	**2011-2015**	**After 2015**
Assessment of economic costs of carbon tax (mostly general equilibrium effects)	Kaufmann (1991) – World; Herber and Raga (1995) – EU; Goulder (1995) – US; Jayadevappa, and Chhatre, (1995) – India; Proost and van Regemorter (1992) – Belgium; Pezzey (1992) – EU; Bossier and De Rous (1992) – Belgium; Agostini et al. (1992) – Europe	Bovenberg and Goulder (1997) – US; Parry (1997) – US; Zhang (1998) - China; Goulder (1998) – US; Fisher-Vanden (1997) – India; Bovenberg and Goulder (1996) – US	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; 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.	Parry and Mylonas (2017) – Canada; Pradhan et al. (2017) - India; Liu et al. (2017) -Guangdong, China; Zhang et al. (2016) - China; 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) – UK; Callan et al. (2009) – Ireland; Hassett et al. (2009) – US; Verde and Tol (2009) – Ireland; Fullerton and Heutel (2007) – Japan; Brenner et al. (2007) - China	Rausch and Reilly (2015) - US; Williams et al. (2014) - US; Bureau (2011) France	Renner (2018) – Mexico; Farrell (2017) – Ireland; Rosas-Flores (2017) – Mexico; Rezai,and Van der Ploeg (2016) – World; Beck et al. (2016) – British Columbia, Canada
Tax revenue and recycling schemes	Parry (1995) – US; Jaeger (1995) – global	Goulder et al. (1997) -US; Parry et al. (1999) -US; Parry and Bento (2000) - US; McKitrick (1997) – Canada; Welsch, (1996) – Germany	Galinato and Yoder (2010) – US; Lu et al. (2010) – China; Bento et al. (2009) – US; Kiuila and Markandya (2009) -Estonia; Timilsina and Shrestha (2007) – Thailand; Metcalf (2007) – US; Parry (2003);	Jorgenson et al. (2015) -US; McKibbin et al. (2015) - US; Rausch and Reilly (2015) - US; Tuladhar et al. (2015) - US; Beck et al. (2015)-British Columbia; Williams et al. (2014) - US; Orlov and Grethe (2014) - Russia; Timilsina et al. (2011) – World;	Carl and Fedor (2016) – World; Rivera et al. (2016) – Mexico; Verde et al. (2016) -EU

			Goodstein (2003) - world.	Kallbekken et al. (2011) – experimental work	
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) - US; Trachtman (2017) - US; Gray and Metcalf (2017)-US; Siriwardana et al. (2017) - Australia; Bohringer et al. (2017a) – US and Canada; Bohringer et al. (2017b) - 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. (2012) - World; Aldy and Stavins (2012) - World; Clarke (2011) - Australia.	Aldy et al. (2017), Hafstead et al. (2017), Aldy (2017b)
Carbon tax vs. other policies			Timilsina (2009); Metcalf (2009a); Aldy et al. (2008); Grimaud and Lafforgue (2008); Green (2008); Gerlagh and van der Zwaan (2006); Kim et al. (2004); Bohringer et al. (2003); Parry (2003)	Zakeri et al. (2015); Goulder and Schein (2013); Wirl (2012); Levin et al (2011); Murphy and Jaccard (2011); McKibbin (2011)	Fried (2018)
Sectoral studies	Newbery (1992)	Rosendahl (1996)	Guthrie and Kumareswaran (2009); Shrestha et al. (2008); Tol (2007); Floros and Vlachou (2005); Schneider and McCarl (2005); Schunk and	Raux et al. (2015); Rivers and Schaufele (2015); Klier and Linn (2015); McKibbin (2014); Li et al (2014); Martin et al. (2014); Keen et al. (2013); Choe (2013); Chernenko (2013); Caurla et	Tsai et al. (2017)

			Hannon (2004) Simshauser and Docwra (2004)	al. (2013); Lee et al. (2013); Di Cosmo et al. (2013); Barua et al. (2012)	
Perception towards 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	Baranzini and Carattini (2017); Carattini et al. (2016) – 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 vs international carbon tax	Bohringer 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

Economists started to discuss the potential use of carbon tax to address global climate change much earlier than the international communities, particularly the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) established the Intergovernmental Panel on Climate Change (IPCC) in 1988 to prepare reviews and recommendations on the science of climate change, its potential social and economic impact, and mitigation measures. William Nordhaus of Yale University, might be the first economist explicitly discussing carbon tax to control global climate change. In his 1977 AER paper, he explains how would the global warming caused by the increased concentration of CO_2 emissions impact economic growth and suggests carbon tax as one of the policy instruments to address the problem (Nordhaus, 1977).

2.1.1. Early Literature on the Carbon Tax (1991-1995)

Academics started to give more attention to the climate change mitigation policies around the same time the United Nations established a separate entity, United Nations Framework Convention on Climate Change (UNFCCC) to facilitate international efforts to control climate change. In the first half of 1990s (1991-1995), two types of studies emerged. The first type of studies was theoretical in nature and addressed various issues related to carbon tax, such as type of carbon tax, movement of tax rates, external benefits of carbon tax and effects of carbon tax with and without international cooperation or agreement (see, e.g. Hoel, 1992, 1993a, 1993b, Sinclair, 1992, Newbery, 1992; Wirl, 1994, 1995; Wirl and Dockner, 1995). The second type of studies used empirical or numerical techniques, in most cases, computable general equilibrium (CGE) models, to assess the economic impacts of carbon tax in meeting various levels of CO_2 mitigation at national, regional and global levels (Ingham et al. 1991; Agostini et al. 1992; Bossier and de Rous, 1992; Pezzey, 1992; Proost and van Regemorter, 1992; Symons et al. 1994; Jayadevappa and Chhatre, 1995; Goulder, 1995 and Parry, 1995). The third type of studies discuss various aspects of carbon tax qualitatively (Pearce, 1991; Poterba, 1991, 1993; Oates, 1995).

Theoretical studies are focused on specific issues related to carbon tax. Hoel (1992, 1993a, 1993b;) examines what type of carbon tax, such as that harmonizes domestic taxes or a uniform international tax would be more effective in reducing global CO_2 emissions. They show that although a uniform carbon tax would be more efficient its implementation in practice would be difficult. Instead introducing domestic taxes and allowing them to pay the tax to an international agency in proportion to their CO_2 emissions would be more practical. Newbery (1992) investigates if a separate carbon tax is needed when transportation fuels are already taxed for various purposes; if yes, how to superimpose a carbon tax on existing transportation taxes. Sinclair (1992) and Ulph and Ulph (1994) examine the direction of carbon tax (rising or falling); while Sinclair (1992) shows that a steadily falling carbon tax would be better, Ulph and Ulph (1994) disagrees and shows no general presumption can be made about the direction of movement of a carbon tax. Wirl (1994, 1995) develops a game theoretic approach to analyze behaviors of fossil fuel producers when an international carbon tax is introduced and shows that cooperative GHG mitigation actions ultimately lead to an efficient outcome, whereas non-cooperative strategies would cause significantly different distributional consequences across the countries. Wirl and Dockner (1995) show that carbon taxes not only mitigate climate change but also raise government revenue and benefit consumers by transferring monopoly rents from producers to consumers. Lund (1994) shows that carbon taxes have other effects in addition to mitigating climate change and positive external effects caused through research and development triggered by a carbon tax.

Country or region specific numerical/empirical studies focus mostly on economic implications of hypothetical carbon taxes or emission reduction targets. For example, Ingham et al. (1991) estimate carbon tax rates and their economic implications to meet different targets to reduce CO_2 emissions in the U.K. Bossier and de Rous (1992) and Proost and van Regemorter (1992) analyze general equilibrium effects of various carbon tax rates in Belgium. Agostini et al. (1992) and Pezzey (1992) examine effects of carbon tax in the European Union. Jayadevappa and Chhatre (1995) analyze economic impacts of implementing carbon tax in India. Hamilton and Cameron (1994) estimate the carbon tax rate needed to meet the Rio target for carbon emissions for Canada and its economic implications for different quintiles of households by income. Using the empirical model, some studies (Goulder, 1995; Parry, 1995; Jaeger, 1995) examine how would welfare impacts of a carbon tax change across the different schemes of recycling carbon tax revenues to the economy. Golombek and Braten (1994) analyze, using an empirical model, optimal carbon tax levels and corresponding welfare effects under incomplete international climate agreements.

The early qualitative studies on carbon tax discuss various aspects of carbon tax. For example, Poterba (1991) presents the basic structure of the carbon tax and its distributional impacts across burden income groups. It also discusses the short- and long-run macroeconomic effects of a carbon tax. Poterba (1993) discusses how to design the optimal carbon tax rate and what are the potential risks associated with it. He argues that although the optimal carbon tax equalizes the discounted value of externalities from a ton of carbon emission with the marginal cost of emission reduction with necessary corrections for distributional differences, two uncertainties -- discount rates and estimates of externalities (e.g., damages) -- pose challenges to determine the optimal carbon tax rate. Oates (1995) suggests the base for externality correcting tax, such as a carbon tax, should be the polluting activity itself instead of related activity, he further suggests that the tax should be revenue-neutral and additional revenues should be recycled to reduce distortions created by the existing tax system.

2.1.2. Carbon Tax Literature during 1996-2000

The carbon tax literature during the second half of the 1990s consists of more empirical works than theoretical ones. We found a few theoretical analyses on carbon tax during the 1996-2000 period: Hoel (1996) and Farzin and Tahvonen (1996). Hoel (1996) investigates whether or not carbon tax rates should be differentiated across sectors in an economy and shows that it should not be differentiated across sectors if they can use import and export tariffs on all traded goods. However sectoral differentiation of carbon tax would be optimal if they are prevented from using tariffs on the traded goods. Farzin and Tahvonen (1996) extend the classical Hotelling model to analyze the time path for a carbon tax and how an accumulating atmospheric CO_2 concentration alters the economic logic of the optimal exhaustible resource consumption in general. It finds that the optimal time path for a carbon tax is either decreasing or has an inverted U-shape if the exhaustible model contains a single decaying pollution stock. On the other hand, the optimal time path increases monotonically if the single stock does not decay.

The remaining carbon tax studies during this period are empirical studies. These are: Welsch (1996), Ekins (1996), Rosendahl (1996), Moon (1996), Lewis and Seidman (1996), Bovenberg and Goulder (1996), Bohringer and Rutherford (1997), Mabey and Nixon (1997), Fisher-Vanden (1997), Cornwell and Creedy (1997), McKitrick (1997), Parry (1997), Goulder et al. (1997), Bovenberg and Goulder (1997), Goulder (1998), Zhang (1998), Parry et al. (1999), Kamat et al. (1999), Parry and Bento (2000), Yokoyama et al. (2000). Applying US data in their general equilibrium model, Bovenberg and Goulder (1996) show that optimal environmental tax rates are 6% to 12% below the rates suggested by the Pigovian principle[6] even when revenues from environmental taxes are used to cut distortionary taxes. Similarly, Parry (1997) and Goulder et al. (1997) show that environmental taxes, such as carbon tax, tend to compound the welfare cost of pre-existing tax distortions in the labor market. This is known as the tax interaction effect. However, the revenue raised from the environmental taxes could offset most of the tax interaction effect if the revenues are used to reduce distortionary taxes. This is called the revenue recycling effect. The cost differential between policies that do or do not exploit the revenue recycling effect depends crucially on the extent of emissions reduction. Using a similar approach, Bovenberg and Goulder (1997) show that the welfare impacts of an environmental tax depend on the magnitudes of prior inefficiencies in the existing labor and capital tax system.

One of the most popular carbon tax issues researched during the 1996-2000 period was the 'double dividend hypothesis' which suggests that an environmental tax, such as a carbon tax, has two benefits. First, it reduces environmental pollution and secondly, the revenue recycling effect, which could help reduce the additional distortions caused by the environmental tax in the presence of factor taxes (Goulder, 1995). Using a CGE model of the Canadian economy, McKitrick (1997) finds empirical evidence of a double dividend in Canada where a revenue-neutral swap of carbon taxes for payroll taxes would yield a welfare gain. When environmental tax revenue is recycled to cut existing taxes on tax favored goods (e.g., housing, medical care), Parry and Bento (2000) also find evidence of a double dividend in the United States. Parry et al. (1999) show welfare impacts of a carbon tax and the level of the double dividend depends on preexisting inefficiencies in relative taxation of labor and capital, and the extent to which carbon abatement policies might reduce these inefficiencies by shifting the tax burden from one factor to another.

A few studies measure, using CGE models, country specific economic impacts of carbon taxes. For example, Bohringer and Rutherford (1997) and Welsch (1996) analyze general equilibrium effects of a carbon tax in Germany and the European Union, respectively. Similarly,

[6] Pigovian principle suggests that an optimal environmental tax is equal to environmental damage cost.

Zhang (1998) and Fisher-Vanden (1997) do the same for China and India, respectively. Country specific economic impacts of carbon tax will be discussed in detail in Section 3.1.

2.1.3. Carbon Tax Literature during 2001-2010

Compared to other periods (i.e., before 2001 or after 2010), not many studies were carried out on carbon tax over the 10 years during the 2001-2010 period.

There are only a few studies that focus on assessing economy-wide impacts or general equilibrium effects of a carbon tax during this period. These are Wissema and Dellink (2007) for Ireland; Matsumoto and Fukuda (2006) for various regions of the world; and Timilsina and Shrestha (2002) for Thailand. Studies analyzing revenue recycling schemes are: Galinato and Yoder (2010) that investigates recycling carbon tax revenue to clean or low emitting sectors in the United States; Lu et al. (2010) that compares various schemes to recycle carbon tax revenues in China; Bento et al. (2009) that investigates effects of recycling carbon tax for correcting urban externalities in the United States; Metcalf (2007) that analyzes impacts of carbon tax revenues to cut corporate tax rates in 58 industries in the United States; Timilsina and Shrestha (2007) that compares four revenue recycling schemes (public consumption, household consumption, labor tax cut and excise tax cut) in Thailand; and Kiuila and Markandya (2009) that compares several revenue recycling schemes in Estonia.

Studies that investigate distributional analysis during the 2001-2010 period include Feng et al. (2010) for the United Kingdom; Verde and Tol (2009) and Callan et al. (2009) for Ireland; Hassett et al. (2009) for the United States; Fullerton and Heutel (2007) for Japan; and Brenner et al. (2007) for China. All these industries except Fullerton and Heutel (2007) shows the distribution of carbon tax impacts across households by income. Fullerton and Heutel (2007) relate the distribution of carbon tax impacts across industries based on substitution possibility among their inputs and carbon intensities of the industries. Studies examining competitiveness and introducing border tax adjustments are: Cloete and Robb (2010) for South Africa; and Lockwood and Whalley (2010), Elliott et al. (2020) and Clark (2011) for different regions in the world.

Several studies published during the 2001-2010 period compare carbon tax with other climate change mitigation policies. Metcalf (2009a) compares carbon tax with various low carbon subsidy schemes in the United States. Timilsina and Shrestha (2009) compare carbon tax with a unique CDM scheme where a developing country can export its emission mitigation from the carbon tax in Thailand. Aldy et al. (2008), Green (2008) and Kim et al. (2004) compare carbon tax with carbon cap and trade policy. Grimaud and Lafforgue (2008) compare carbon tax with an R&D investment for endogenous technological change. Gerlagh and van der Zwaan (2006) compare carbon tax with subsidies to renewable energy and carbon capture and sequestration. Bohringer et al. (2003) compare carbon tax with an offset mechanism, Joint Implementation (JI). Parry (2003) compares carbon tax and ETS in terms of their revenue recycling implications.

A few studies during 2001-2010 present a detailed qualitative discussion of carbon tax issues during this period. Two notable studies are Aldy et al. (2010) and Ekins and Baker (2001). The latter is one of the very few early studies discussing carbon tax in detail. Metcalf (2009b) highlights key design issues of carbon tax. Some studies during this period analyze carbon tax from a sectoral perspective. Guthrie and Kumareswaran (2009) examine carbon tax for reducing GHG emissions from the forestry sector. Shrestha et al. (2008) and Floros and Vlachou (2005) do the same for energy demand sectors in Thailand and Greece, respectively. Schneider and McCarl (2005) and Schunk and Hannon (2004) analyze effects of carbon taxes in the agriculture sector in the United States. Simshauser and Docwra (2004) investigate the impacts of carbon taxes on fuel mix in the electricity generation sector in Tasmania, Australia.

A number of studies during the 2001-2010 period analyze specific issues of carbon tax, such as, role of carbon tax for innovation and technological change (Golombek et al. 2010; Gerlagh et al. 2009; Baker and Shittu, 2006; Gerlagh and Lise, 2005), health benefits of carbon tax in Thailand (Li (2006)), impacts of carbon tax when climate change affects productivity (Jaeger (2002). Liski and Tahvonen (2004) analyze the optimal emission tax for a stock pollutant when the pollutant flow is also regulated by a resource-exporting cartel. Bye and Nyborg (2003) compare differentiated carbon tax, a system implemented in Norway with a uniform carbon tax system.

2.1.4. Carbon Tax Literature during 2011-2015

The five years during the 2011-2015 period witnessed the large number of studies on various topics related to carbon tax. These topics can be broadly classified into the following categories: distributional effects of carbon tax; unilateral carbon tax, competitiveness and border tax adjustment; estimation of economic costs of carbon tax; revenue recycling; reviews of carbon tax in general; carbon tax focusing on selected sectors and specific topics on carbon tax. Since most of these issues (i.e., impacts of carbon tax, revenue recycling, BTA) will be discussed separately later, we do not discuss them here in detail.

The studies assessing the impacts of carbon tax in general are: Cabalu et al. (2015) for Philippines, Nekrasenko et al. (2015) for Ukraine; Allan et al. (2014) for Scotland; Espinosa and Fornero (2014) for Chile; Mahmood and Marpaung (2014) for Indonesia; Meng et al. (2013) for Australia; Conefrey et al. (2013) for Ireland and Devarajan et al. (2011) for South Africa. Studies examining the carbon tax revenue recycling schemes during the 2011-2015 period include Jorgenson et al. (2015); McKibbin et al. (2015); Rausch and Reilly (2015); Tuladhar et al. (2015); Williams et al. (2014); Orlov and Grethe (2014); Bureau (2011) and Timilsina et al. (2011). Among these, the first four studies (Jorgenson et al., 2015; McKibbin et al. 2015; Rausch and Reilly, 2015; Tuladhar et al. 2015) were published in a 2015 special issue of the National Tax Journal (National Tax Journal, Volume 68, Issue 1) when the journal published the special issue to present various studies analyzing potential fiscal implications of carbon tax in the United States. One of the main schemes considered in these studies was the use of carbon tax revenue to cut fiscal deficit and debt. The other schemes included vary across studies; more common revenue recycling schemes among these studies were capital tax cut, labor tax cut and lump-sum transfer to households.

Studies examining the border tax adjustments during this period include Tang et al. (2015), Keen and Kotsogiannis (2014), Mattoo et al. (2013), Burniaux et al. (2013); Li et al. (2013), Li and Zhang (2013), Dong and Whalley (2012a), Kaufmann and Weber (2011). Among these studies, a few of them discuss issues related to BTA using theoretical models (Eichner and Pethig, 2015; Keen and Kotsogiannis, 2014) or in general (McLure, 2014; Moore, 2011; Kaufmann and Weber, 2011) or assess the impacts of BTA in a particular country's context (Tang et al. 2015; Alton et al. 2014; Mattoo et al. 2013; Burniaux et al. 2013; Li et al. 2013; Li and Zhang, 2013, Yan and Whalley, 2012). Other studies focusing on BTA examine specific topics related to BTA (Elliott and Fullerton, 2014; Fischer and Fox, 2012).

Studies published during the 2011-2015 offering general reviews of carbon tax include Jenkins (2014); Tietenberg (2013); Elgie and McClay (2013); Parry et al. (2012); Aldy and Stavins (2012) and Clarke (2011). While Clarke (2011) and Elgie and McClay (2013) review the carbon tax in the context of Australia and Canada, respectively, other reviews are more general discussing various issues of the carbon tax such as rate design, revenue recycling, distributional impacts, etc.

A large number of studies published during the 2011-2015 period deals with specific issues related to carbon tax. For example, Parry et al. (2015a) and Parry et al. (2014) measure other environmental benefits, particularly local environmental benefits, of carbon tax. Murray and Rivers (2015), Gevrek and Uyduranoglu (2015), Bumpus (2015) and Lo et al. (2013) measure public perception towards carbon tax policy in Australia, Canada and Turkey. Zakeri et al. (2015), Goulder and Schein (2013), Strand (2013) and Maruyama (2011) compare carbon tax with cap and trade policy. Murphy and Jaccard (2011) and McKibbin (2011) compare carbon tax with energy efficiency standards.

Several carbon tax studies published during the 2011-2015 period focusses on a particular sector, such as, Raux et al. (2015, Rivers and Schaufele (2015) and Klier and Linn (2015) analyzing carbon tax to reduce emissions from the transport sector; McKibbin (2014) and Li et al (2014) and Chernenko (2013) analyze impacts of carbon tax on the power sector; and Caurla et al. (2013) and Barua et al. (2012) examine the impacts of carbon tax on the forestry sector.

2.1.5. Recent Literature on Carbon Tax (after 2015)

Recent empirical literature on carbon tax can be classified into three streams. The first stream focusses on assessing economic costs of carbon tax or general equilibrium effects of carbon tax (Parry and Mylonas, 2017; Pradhan et al. 2017; Zhang et al. 2016; Nurdianto and Resosudarmo, 2016; van Heerden et al. 2016; Benavente and Miguel, 2016; Pereira et al. 2016; Calderon et al. 2016; Rivera et al. 2016). The second stream examines competitiveness issues (Aldy, 2017; Trachtman, 2017; Gray and Metcalf, 2017; Siriwardana et al. 2017; Bohringer et al. 2017a; Bohringer et al. 2017b; Kortum and Weisbach, 2017). The third stream deals with some specific issues of carbon tax, such as the green paradox, revenue recycling, distributional effects

(Yamazaki, 2017; Jakob et al. 2016; Aghion et al. 2016; d'Autume et al. 2016; and van der Ploeg and de Zeeuw, 2016); Fried (2018).

The studies assessing the cost of carbon were carried out at the regional level, national level and even at sub-national levels. Nurdianto and Resosudarmo (2016) assessed the economic costs of a carbon tax at the regional level for the member countries of ASEAN (Association of South East Asian Nations). Pradhan et al. (2017) analyzed impacts of a carbon tax on international trade of China and India. van Heerden et al. (2016), Benavente (2016), Pereira et al. (2016), Calderon et al. (2016) and Rivera et al. (2016) assess the impacts of carbon tax at the national level in South Africa, Chile, Portugal, Colombia and Mexico, respectively. Parry and Mylonas (2017) and Zhang et al. (2016) analyzed the impacts of carbon tax at the provincial level in Canada and China, respectively. More details of some of these studies are presented later when we discuss the economic costs of carbon tax in Section 3.1.

The issues of border tax adjustments in relation to carbon taxes, and compensating measures are getting increasing attention in the recent literature on carbon tax. The second issue of the National Tax Journal published in 2017 (National Tax Journal, Volume 70, Issue 2) published four papers on these issues (Aldy, 2017; Trachtman, 2017; Gray and Metcalf, 2017; Kortum and Weisbach, 2017). These studies examine alternative options to minimize the potential competitiveness impacts of a hypothetical unilateral carbon tax in the United States. Siriwardana et al. (2017) examine the issue for Australia, and Bohringer et al. (2017a and 2017b) analyze this issue from a global perspective. We will discuss in detail the competitiveness impacts and compensating measures later in this paper (Sections 3.2 and 4.2).

The specific issues of carbon tax analyzed in the recent literature (after 2015) vary widely. Fried (2018) estimates the effect of carbon tax to innovation, which in turn, reduces the size of the carbon tax. Yamazaki (2017) investigates the employment impact of British Columbia's carbon tax introduced in 2008. Jakob et al. (2016) estimate the size of revenue from a carbon tax required to limit global warming to below 2 degrees Celsius and compare it to the global investment needed to provide basic infrastructure for all. Aghion et al. (2016) provide evidence of the auto industry's increasing investment on clean technologies in response to higher tax-inclusive fuel prices to imply that carbon tax promotes clean automobiles. d'Autume et al. (2016) investigate whether the carbon tax should be uniform universally or differentiated across economies. van der Ploeg and de Zeeuw (2016) examine how would the level of vulnerability to climate change and stage of development affect a country's cooperation to the global efforts to mitigate climate change.

2.2 Methodologies Used in the Carbon Tax Literature

The methodologies used in the carbon tax literature can be divided into three groups: theoretical, empirical (numerical) and review or qualitative technique. The empirical or numerical models used to analyze carbon tax issues can be divided into multiple groups based on the methodology used, such as, general equilibrium models (e.g., CGE models), input-output models, partial equilibrium models, optimization models and econometric models. It is interesting to note that the general equilibrium approach, particularly the computable general equilibrium model (CGE), is the most common analytical tool to analyze all major issues related to carbon tax, such as economics of carbon tax, revenue recycling schemes, distributional impacts, border tax adjustments. All these issues will be discussed in detail later in this paper.

Selection of an analytical tool depends on the objective of a study. In early years (i.e., 1990s) many studies analyzing carbon tax issues used theoretical approaches (e.g. Sinclear, 1992; Newbery, 1992; Hoel, 1992; Hoel 1993a, Hoel 1993b, Wirl, 1994, Wirl, 1995; Wirl and Dockner, 1995; Hoel, 1996; Farzin and Tahvonen, 1996). These studies investigate questions which are generic across countries and economic sectors. For example, Hoel (1992, 1993a, 1993b) investigated whether a uniform international carbon tax would be better to domestic carbon tax systems which are harmonized across countries. Sinclair (1992), Ulph and Ulph (1994) Farzin and Tahvonen (1996) examined whether a carbon tax rate should be rising or falling over time. However, more and more researchers preferred empirical studies to analyze issues related to carbon tax. Over the last 30 years, the body of carbon tax literature expanded exponentially, however, carbon tax studies using theoretical approaches were limited. Carbon tax studies published after 2000 that use theoretical approach include Liski and Tahvonen (2004), Baker and Shittu (2006), Wirl (2007), Golombek et al. (2010), Dullieux et al. (2011), Wirl (2012), Strand (2013), Weitzman (2014), van der Ploeg and Withagen (2014), van der Ploeg (2015), Andrade de Sa and Daubanes (2016), d'Autume et al. (2016). These studies focus on specific issues, such as how would an international carbon tax affect resource rents of oil producing countries (Liski and Tahvonen, 2004; Dullieux et al. 2011); firms' research and development response to carbon tax (Baker and Shittu, 2006; Golombek et al. 2010) and trade-offs between fossil resource extraction and clean and renewable energy adoption (van der Ploeg and Withagen, 2014; van der Ploeg, 2015; Andrade de Sa and Daubanes, 2016); uniformity of carbon tax rates across countries (d'Autume et al. 2016).

While theoretical models are normally robust in predicting qualitative results (i.e., whether a carbon tax increase or decrease welfare), they cannot predict the quantity or magnitude (e.g., how much GDP or welfare does a carbon tax change in an economy). Policy makers are more interested to see the quantitative results of a carbon tax, such as if a carbon tax is introduced in an economy, how much percentage of GDP it increases or decreases, how much additional revenues it generates. A carbon tax affects economic agents (i.e., households, firms, governments) differently, its impacts would also vary across production sectors (e.g., agriculture, electric power generation, service sector). Numerical models are needed to measure these quantitative impacts. The choice between theoretical versus empirical models is not the superiority in terms of quality of one approach versus the other, rather it is the objective of the research question in hand.[7] The use of empirical models, particularly, CGE models, has rapidly increased over the last three decades to analyze carbon tax issues to capture quantitative impacts of carbon tax, which are heterogenous impacts across sectors and between sectors and agents. Table 2 clearly indicates the preference of CGE models to other models in carbon tax analysis. Information presented in Tables 1 and 2 shows that not only studies for developed countries but also a large number studies for developing countries have analyzed carbon tax using CGE models.

[7] The highly simplified approach used in theoretical models (for example, dividing the entire economy into two sectors ignoring the heterogeneity among the sectors or two types of fuels, such as clean and dirty) sometimes produces results that do not hold in the real world where sectoral heterogeneity in terms of their relative sizing, emission intensity, tradability, substitutability and factor intensity causes impacts of a carbon tax across the sectors significantly that are different.

Table 2. Classification of carbon tax literature by analytical methodology

Main category	Sub-Category	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		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) for Guangdong, China; Levin et al. (2011) for Georgia, US; Shrestha et al. (2008) for Thailand, Simshauser and Docwra (2004) for Queensland, Australia
Input-output modeling		Jiang and Shao (2014), Sun and Ueta (2011) and Wang et al. (2011) for China; Bordigoni et al. (2012) for EU, Callan et al. (2009) and Verde et al. (2009) for Ireland; Metcalf (2007) for US; Bossier and de Rous (1992) for Belgium, Jayadevappa and Chhatre (1995) for India, Moon (1996) for the Republic of Korea
General equilibrium modeling	Single country static model	Benavente (2016) for Chile; Coxhead et al. (2014) for Vietnam; Dissou and Siddiqui (2014) for Canada, Meng (2013, 2014, 2015) for Australia; Devarajan et al. (2011) for South Africa; Timilsina (2009), Timilsina and Shrestha (2007) and Timilsina and Shrestha (2002) for Thailand; Miyata et al. (2013) for Makassar City, Indonesia; Kiuila and Markandya (2009) for Estonia; Wissema and Dellink (2007) for Ireland; Bohringer et al. (2003) for Germany and India; Kamat et al. (1999) for Susquehanna River Basin of the US; Bohringer and Rutherford (1997) for Germany; McKitrick (1997) for Canada
	Single country recursive dynamic	Pradhan et al. (2017) for India; van Heerden et al. (2016) for South Africa; Pereira et al. (2016) for Portugal; Cabalu et al. (2015) for Philippines; Mahmood and Marpaung (2014) for Pakistan; Li et al. (2014), Liang and Wei (2012), Lu et al. (2010) and Zhang (1998) for China; Li (2006) for Thailand; Kim et al. (2004) for Korea; Fisher-Vanden (1997) for India
	Single country intertemporal	Jorgenson et al. (2015) for U.S.; Williams et al. (2014) for US; 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) for China; Nurdianto and Resosudarmo (2016) for ASEAN; Zhou et al. (2013) for Japan; Dong and Whalley (2012a,b)
	Multi-country/region recursive dynamic	Rausch and Reilly (2015) for US, Allan et al. (2014) used for Scotland, Proost and van Regemorter (1992) used for Belgium
	Multi-country/region intertemporal	Tuladhar et al. (2015) for US, Welsch (1996)

	Global static	Li et al. (2014, 2013) used for China; Orlov and Grethe (2014) used for Russia; Burniaux et al. (2013) for global; Mattoo et al. (2013) for global, Fischer and Fox (2012)
	Global recursive dynamic	Rivera et al. (2016) used for Mexico; Elliott and Fullerton (2014); Dellink et al. (2013) for global; Timilsina et al. (2011) for global; Elliott et al. (2010) for US
	Global intertemporal	McKibbin et al. (2015, 2011) used for U.S., 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) for
Qualitative analysis		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), Weisbach and Metcalf (2009), Whitesell (2007), Matsumoto and Fukuda (2006), Ekins and Baker (2001), Pearce (1991), Poterba (1991; 1993), Oates 1995
Econometric approach		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)

A CGE model is based on general equilibrium theory pioneered by the French mathematical economist Leon Walras[8] that can be solved numerically. A CGE model represents behavior of all economic agents (producers, consumers, governments and foreign). The number of producers (sectors) explicitly modeled depends on the research question investigated and data availability.[9] A common practice in CGE modeling is using the social accounting matrix (SAM) as the main database to begin. A SAM is an account reflecting the circular transactions and transfers, in terms monetary value, between and within economic agents in an economy (e.g., outputs from one production sector consumed by other production sector, final consumers, export markets, households supplies labor and capital to firms to receive wages and rents; government collect taxes and make transfers, etc.) (Pyatt, 1998). Since the connections of every economic agent (producers, consumers, governments, foreign or international trade) are explicitly reflected in a CGE model, it is capable of capturing changes in all variables representing the behavior of the economic agents and measures of economic output or household welfare when a variable somewhere in the economy is altered due to a policy or market change.

As mentioned above CGE models are widely used analyzing carbon tax issues in the literature. There exists a large variation in the CGE models used. CGE models can be classified into static and dynamic. The main difference between static and dynamic models is that while the latter allows structural adjustment, the former simply assume it. Static models are often single period models and realistically there does not exist enough time for the structural adjustment. Still static models assume mobility of factors from one sector to another in response to policy or market shock. Dynamic models allow time for such adjustment, however most dynamic models connect static models of multiple periods and call it 'recursive dynamic'. Intertemporal dynamic models have attempted to address this limitation. Depending upon spatial or geographical coverage, CGE models can be classified as single country, multi-region or multi-country and global models. The first represents a country as a single economy, the second allows multiple economies within a country (e.g., provincial or state economies) or considers multiple countries

[8] Walras' general equilibrium theory implies that the sum of the values of excess demands across all markets must equal zero. This theory, first published in French in 1989 (Éléments d'économie politique pure), was published in English in 1954 (Walras, 1954). The first computable general equilibrium model was developed by Leif Johansen in late 1950s (Johansen, 1960).

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

with each country represented by a single economy. The global models cover the world economy with the representation of economies of countries or groups of countries as needed or supported by data availability. Table 2 presents the existing carbon tax literature that uses CGE models under these categories. As shown in this table, most carbon tax studies using CGE models employ either a single country static model or single country recursive dynamic model. Examples of the former group are Benavente (2016) for Chile, Coxhead et al. (2014) for Vietnam, Devarajan et al. (2011) for South Africa; Timilsina and Shrestha (2007) for Thailand, Kiuila and Markandya (2009) for Estonia. Examples for single country recursive dynamic models are: Pradhan et al. (2017) for India, van Heerden et al. (2016) for South Africa, Cabalu et al. (2015) for the Philippines, Mahmood and Marpaung (2014) for Pakistan, Li et al. (2014 for China. Most advanced CGE models (intertemporal models) are developed either for developed countries (e.g., McKibbin et al. 2015) or are developed for the world level with some regional disaggregation.

The input-output (I-O) models are structurally similar to CGE models as both are based on I-O tables,[10] they are however, different from CGE models in many respects.[11] CGE models are flexible in choosing functional forms to represent agents' behavior and allow substitutions between factors, between factors and intermediate inputs, between intermediate inputs themselves, I-O models normally uses fixed coefficients (or Leontief[12] functional form) and do not allow substitution possibilities in response to price changes. Moreover, I-O models are not capable to reflect the supply constraints.[13] These restrictions do not allow an I-O model to realistically estimate impacts of carbon tax to an economy. Moreover, an I-O model is incapable of measuring many variables, such as household welfare, producers and consumer prices, fiscal impacts and impacts on international trade. Knowing potential impacts of carbon tax on these variables is important when a decision is made whether or not to introduce a carbon tax to an economy. Examples of studies using I-O models to examine impacts of carbon tax are: Bossier

[10] A CGE model is based on SAM, which is an extension of I-O tables.
[11] Rose (1995) provides a good account of difference between these two types of models.
[12] Wassily Leontief, the father of the I-O modeling approach, who received the Nobel Prize in 1973 for his I-O analysis.
[13] In fact, CGE models are further developments of I-O models to relax many of latter's constraints. Although Rose (1995) provides a good account of making the I-O approach more flexible, most I-O models used to analyze carbon tax uses are not found to adopt the flexibilities.

and de Rous (1992) for Belgium, Jayadevappa and Chhatre (1995) for India, Metcalf (2007) for the United Sates, Jiang and Shao (2014), Sun and Ueta (2011) and Wang et al. (2011) for China.

Partial equilibrium models are flexible like CGE models. However, they are different from the CGE model in many respects. First, the coverage of economic agents in a partial equilibrium model is not as extensive as in the case of general equilibrium models. For example, they model behaviors of some agents and assume no change in other agents due to the policy change. Even if a partial equilibrium model covers all economic agents (see e.g., in Calderon et al. 2016, Conefrey et al. (2013),), it does follow Walrasian condition to close the model. Quite often, partial equilibrium models focus on particular sectors. For example, Schneider and McCarl (2005) and Schunk and Hannon (2004) use a partial equilibrium approach to analyze carbon tax in the agriculture sector; Keen et al (2013) use a partial equilibrium model to analyze carbon tax in the aviation sector; Caurla et al (2013) and Guthrie and Kumareswaran (2009) do the same for the forestry sector; Rosendahl (1996) uses a partial equilibrium model to analyze impacts of carbon tax on oil price. Partial equilibrium models are the main analytical tools in the carbon tax if the objective of the study is to analyze some specific issues related to carbon tax. For example, Agostini et al. (1992) use a partial equilibrium model to investigate the role of carbon tax in stimulating energy saving and fuel substitution; Gerlagh et al. (2009), Gerlagh and Lise (2005) use a partial equilibrium approach to analyze the impacts of a carbon tax on technological change.

Optimization models are used mainly to analyze impacts on the energy supply mix in a country or fuel mix in its power generation system. It uses an optimization technique to find the least cost energy supply mix or electricity generation mix for a given time period in the future satisfying technological, environmental and other constraints. Examples of optimization models analyzing carbon tax are: Liu et al. (2017) that applies a multi-objective optimization model to analyze impacts of carbon tax on the energy-intensive sectors of Guangdong province, China; Levin et al. (2011) that uses a MARKAL model for the U.S. state of Georgia; Chernenko (2013) uses a linear programming model to analyze impacts of carbon tax in fuel mix for power generation in the Russian Federation; Simshauser and Docwra (2004) uses a dynamic optimization model to assess impacts of carbon tax in the electricity sector in Queensland, Australia; Shrestha et al. (2008) uses an energy system optimization model to analyze impacts of carbon tax in Thailand.

Econometric methods are used for two purposes. First to observe the impacts of carbon tax on a fuel or CO_2 emissions in countries or regions where carbon tax has been introduced for many years. Examples are Lin and Li (2011) that analyze the reduction of CO_2 intensity in Scandinavian countries where carbon tax has been introduced since thr early 1990s; Bureau (2011) that analyzes household response to carbon tax in France where it has been introduced for many years; Bumpus (2015) that analyzes firms' response towards carbon tax in British Colombia where carbon tax has been introduced over a decade. The second objective of using econometric approach in carbon tax studies is to analyze stakeholders' or public opinion about carbon tax policies. Examples are: Lo et al. (2013) in Australia, Pillay and Buys (2015) in South Africa.

3. Impediments to the Carbon Tax

Implementation of carbon tax in practice is limited. So far, only 20 economies around the world have implemented carbon tax. Even if it has been introduced, the tax rates in some countries (e.g., Mexico, Chile) are small, they might not be able to make noticeable impacts in reducing GHG emissions. This section highlights, based on knowledge available from the large body of carbon tax literature, why countries are reluctant to introduce carbon tax. Among the several reasons, the principle reasons are economic and welfare costs of carbon tax, threat to competitiveness of carbon intensive trade exposed sectors and potential leakage of emissions when a carbon tax is introduced unilaterally. These factors are discussed in detail in the following sub-sections with empirical evidence.

3.1 Costs of the carbon tax

One of the main reasons for the reluctance or opposition to introduce carbon tax in an economy is its potential adverse economic impacts, such as loss in overall economic outputs (GDP) and social welfare. A large number of studies have measured potential economic loss due to a hypothetical (in some cases actual) carbon tax. Table 3 presents examples of economic losses estimated by various studies. Unless the benefits of climate change mitigation from a carbon tax are quantified and accounted for, a carbon tax causes a positive economic cost. Since existing empirical studies on carbon tax do not account for the benefits of mitigating climate change, the common findings are carbon taxes cause the economy to shrink thereby reducing sectoral economic outputs (e.g., sectoral outputs) and national economic output (GDP), international trade and household welfare. Below we present results from some studies to substantiate the discussion.

Using a static CGE model, Meng et al. (2013) assess, ex-ante, the economic impacts of the actual carbon tax introduced by the Julia Gillard's labor government in Australia in July 2012. The study found that the AS$23/t$CO_2$ tax with the exemption of agriculture, road transport, and household sectors, would cause 0.6% loss of GDP when government uses the tax revenue for public consumption. The GDP loss would be slightly lower (0.5%) when the tax revenue is recycled to households as a lump-sum rebate to partially compensate the households from the adverse impacts of carbon tax. The Australian carbon tax was, however, withdrawn just after two years when the Conservative Party came to power under Tony Abbott's leadership.

Fisher-Vanden et al. (1997) estimate, using a dynamic CGE model, the required carbon tax path during 1995-2030 and corresponding economic impacts to limit India's CO_2 emissions in 2030 at the level of: (a) 1990 emissions, (b) two times of 1990 emissions and (c) three times of 1990 emissions. It finds that if India's emission in 2030 were to be limited at three times the 1990 level, a carbon tax of rate (expressed in 1985 price) of $2/tC was needed in 2015 and increased the rate to US$15/tC in 2025 and further to US$25/tC in 2030. These carbon taxes would cause India's GDP to drop by slightly (0.1%) in those years. For a more stringent emission reduction target, for example, to limit the emissions in 2030 at the level of 1990, the carbon tax was required to be introduced much earlier, in 1995 and at much higher rate. In this case, the required carbon tax rates were $40, $225 and $1,110 per ton of carbon in 1995, 2015 and 2030, respectively. The annual GDP losses from the baseline were 1.8%, 4.6% and 6.3% in 1995, 2015 and 2030, respectively.

Table 3. Examples of economic costs of carbon tax from selected studies

Economy	Study	Carbon tax rate or emission reduction target	Impacts
Australia	Meng et al. (2013)	AS$23/t$CO_2$ introduced by Julia Gillard's Labor government in July	0.59% of GDP loss in the absence of compensation mechanism and 0.48% of GDP loss when tax revenue is used to compensate the economic

		2012[14]; it was estimated to reduce 12% emission reduction from the baseline	loss by recycling the revenue to the economy for various purposes
Canada	McKitrick (1997)	CN$19.6 to 21.7 per ton of CO_2 to reduce 12.5% of CO_2 emission from the baseline	GNP loss of 0.9, 0.8, 0.5 and 0.3 percent from the baseline when tax revenue is recycled for, respectively, to cut corporate income tax, lump-sum transfer to households, to cut taxes on goods and services and to cut personal income tax
	Parry and Mylonas (2017)	CN$50/t$CO_2$ needed for meeting Canada's NDC (30% reduction of CO_2 emission in 2022 from 2005 level)	Total welfare costs (without subtracting benefits of local environmental benefits) would vary 0.15–0.3percent of GDP in Quebec and Ontario to more than 0.6 percent of GDP in the other, more emissions intensive, provinces
Chile	Benavente (2016)	$26/t$CO_2$ carbon tax for 20% reduction of CO_2 emission from the baseline	2.3% of GDP loss when tax revenue is recycled to households through a lump sum transfer
China	Lu et al. (2010)	Carbon tax rates varying from 50 to 300 Yuan per ton of carbon	50, 150 and 200 Yuan/tC carbon tax would cause 0.19, 0.56 and 1.1% of GDP from the baseline, when the tax revenue is used by the government.
	Zhang et al. (2016)	20-60 Yuan per ton of CO_2 tax in Henan, Fujian and Chongqing provinces of China; The Yuan 60/tCO2 tax in these provinces would reduce 26%, 25% and 14% of CO_2 emissions from the baseline in Henan, Fujian and Chongqing provinces respectively	A 60 Yuan/tCO_2 tax would cause 0.82, 0.23 and 0.16 percent reduction of GDP from the baseline in Henan, Chongqing and Fujian, provinces respectively when governments spend the carbon tax revenue
Colombia	Calderon et al. (2016)	Carbon tax $50/t$CO_2$ in 2050; corresponding CO_2 reduction from the baseline emissions - 45%	GDP losses of 2.3% to 3.4% from the baseline in 2050
India	Fisher-Vanden et al. (1997)	Carbon tax rate US$/tC (1985 price) for limiting CO_2 emissions of 2030: • 40, 225 and 1,110 in 1995, 2015 and 2030 for limiting at 1990 level • 8, 36 and 162 in 2005, 2015 and 2030 for limiting at two times of 1990 • 2, 15 and 25 in 2020, 2025 and 2030 for limiting at three times of 1990	% annual GDP loss from the baseline for limiting CO_2 emissions of 2030: • 1.8, 4.6 and 6.3 in 1995, 2015 and 2030 when limited at 1990 level • 0.3, 1.1 and 2.9 in 2005, 2015 and 2030 when limited at two times of 1990 • About 0.1 in 2020, 2025 and 2030 for limiting at three times of 1990
Ireland	Wissema and Dellink (2007)	Carbon tax with rate 0 - 40 euros per tonne of CO_2; 25 and 40€/tCO_2 carbon tax reduce 42% and 50% of	25 and 40€/tCO2 carbon tax reduce 0.8% and 1.3% of welfare from the baseline

[14] The carbon tax, introduced in 2012, was withdrawn by Tony Abbott's Conservative government after 2 years in operation in July 2014.

		CO_2 emissions from the baseline, respectively	
Mexico	Rivera et al. (2016)	Increasing carbon tax with rates US\$100/tCO_2 in 2025 and US\$700/tCO_2 in 2050; 25% and 75% reductions of emissions in 2025 and 2050, respectively	GDP loss of 3% in 2025 and more than 8% in 2050 from the baseline
Pakistan	Mahmood and Marpaung (2014)	Carbon taxes of \$10/tCO_2 to \$80/tCO_2 A \$50/tCO_2 carbon tax reduces 20-22% of CO_2 emissions from the baseline in 2050	A carbon tax with rate \$10, \$50 and \$80 per ton of CO_2 would reduce 0.4%, 2.3% and 3.6% GDP in 2050 from the baseline when revenue is used by the government; The GDP loss would be smaller if the tax revenue is recycled to households as a lump-sum rebate (for \$50/tCO_2 tax rate GDP loss would be 1.5% instead of 2.3%)
Philippines	Cabalu et al. (2015)	A carbon tax of \$US5/tCO_2 to reduce 9.8% CO_2 emissions from the baseline	0.5% of GDP loss from the baseline
Scotland	Allan et al. (2014)	£50/tCO_2 for 37% CO_2 reduction in 2020 from the level of 2000	1.37% reduction of GDP when tax revenue is for public consumption and 0.83% increase in GDP when tax revenue is used to cut income tax
South Africa	Alton et al. (2014)	\$30/tCO_2 carbon tax that causes 41% CO_2 reduction from the baseline	1.65%, 1.07% and 0.59% GDP loss from the baseline when the carbon tax revenue is recycled, respectively for social transfer, cutting sales tax and cutting income tax
	van Heerden et al. (2016)	R120/tCO2-equiv. levy on coal, gas and petroleum fuels	The carbon tax causes net negative impacts on GDP under all scenarios for sectoral exemption and revenue recycling; Recycling the tax revenue to finance production subsidy to industries causes the minimum GDP loss
	Devarajan et al. (2011)	\$12.72/tCO_2 carbon tax to reduce 15% of CO_2 emission from the baseline	0.33% welfare loss from the baseline when revenue is transferred to households as lump-sum rebate
Thailand	Timilsina and Shrestha (2002)	Various carbon tax rates ranging from \$10/tC to \$40/tC with corresponding CO_2 emission reductions of 5% and 14% from the baseline	Welfare loss of 0.25% and 0.75% for the \$10/tC to \$40/tC carbon tax rates, respectively

A carbon tax would produce other environmental benefits besides reducing GHG emissions. One of the main benefits is the reduction of local environmental pollution. One would wonder whether the cost of the carbon tax would be negative if the local environmental benefits are accounted while estimating the net cost of a carbon tax. Parry and Mylonas (2017) examine this issue as well. Simulating a CN\$50/tCO_2 carbon tax that would be needed to achieve the pledge made by Canada under the Paris Agreement (i.e., Canada's NDC), the study finds that the carbon tax causes positive economic costs even if local environmental benefits are accounted for. The welfare loss of carbon tax varies from 0.02% of GDP in Quebec to 0.45% in British Columbia.

The potential impacts of carbon tax presented in Table 1 provide empirical evidence of adverse impacts of carbon tax in various economies. While the magnitude of carbon tax varies significantly how the carbon tax revenue is recycled to the economy, the direction of impact is always negative, with few exceptions (McKitrick, 1997; McKibbin et a. 2015).

Note that the purpose of presenting the economic costs of carbon taxes reported by various studies in Table 1 is to illustrate that a carbon tax causes adverse economic impacts. The economic impacts from these studies cannot be compared to each other for different reasons. For example, the carbon tax rates and corresponding mitigation targets considered in these studies are different; the revenue recycling schemes considered in these studies are different, the studies are carried out in different times periods. Moreover, these studies have used different models and their underlying assumptions are different. Even if a same carbon tax rate is considered for a given time period keeping the same tax design architecture (e.g., the same revenue recycling scheme and similar trend for rate change over time) and a same model is applied to measure economic costs, the economic costs would still be different for the reasons discussed below.

First, the same level of carbon tax could have different level of economic impact, say GDP loss, in different economies because of difference in their economic structures. An economy, which is relatively carbon intensive due to heavy reliance on high carbon intensive fuels (e.g., coal), is expected to face larger economic loss, than a country with a less carbon intensive energy supply system. Considering other factors equal, China, India and South Africa are likely to face higher cuts in their GDP for a given carbon tax rate than France and Norway because carbon intensities of the former economies are higher as they heavily rely on coal, a high carbon content fuel, than the latter economies.

Second, the economic cost of a carbon tax depends on the economics of substitution of carbon intensive fuels with low carbon or no carbon fuels. If low carbon or no carbon fuels are available or can easily be imported in 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 carbon tax. At present, for example, the cost of carbon tax in the U.S. 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. In fact, it is already happening even without carbon tax especially when investors make a fuel choice while building new power plants. The degree of substitution, however, depends on the rate of carbon tax, relative costs of competing fuels (e.g., coal and gas for power generation), stringency of climate policies, etc.

3.2 Competitiveness Concerns and Emission Leakage

The concern on losing competitiveness of domestic industries, especially emission intensive trade exposed industries, is one of the main factors to push back the carbon tax. This concern arises when a country introduces carbon tax but other countries producing competing goods do not. The risks of losing competitiveness undermines political support for a carbon tax (Aldy, 2017). The loss of competitiveness causes industries to move to locations where carbon tax does not exist or the rate is low even if it exists (Jaffe et al. 1995). Sectors that are prone to competitiveness loss due to a carbon tax produce tradable goods and their production processes are energy (or emission) intensive. These sectors are also referred to as ‘emission intensive trade exposed’ or ‘EITE’ sectors in the literature (Bohringer et al. 2017a, Bohringer et al. 2017b; Gray and Metcalf, 2017; Metcalf, 2014).

Using a two-step empirical analysis with a 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 as compared to that of non-energy-intensive industries. The output cuts come from the higher increase of relative prices of energy intensive goods than that of non-energy intensive goods. For the same quality, increasing the price of a good decreases its global market share. They also found that net imports of energy-intensive goods are higher than that of non-energy intensive goods. This means a carbon tax not only reduces the exports of energy-intensive goods but also causes domestic consumers to substitute domestically produced energy-intensive goods with their imported counterparts.

Analyzing the impacts of environmental tax in Vietnam, Coxhead et al. (2014) find that a unilateral environmental tax hurts Vietnam’s competitiveness in global markets not only of energy intensive industries but also of labor-intensive export industries. It would impede job growth in the economy. In evaluating a unilateral climate policy, Bohringer et al. (2012) find that a \$40/tCO_2 carbon tax reduces 2.5% of outputs of energy-intensive, trade-exposed industries.

Several studies find that a carbon tax causes decrease in total exports due to loss of competitiveness. For example, Lu et al. (2010) find, in China, that a carbon tax of 300 yuan (US\$40) per ton of CO_2 would cause more than 3% drop in total exports from the baseline. For about the same level of carbon tax rate (US\$40/tCO_2), Mahmood and Marpaung (2014) find more than 4% drop of total exports (compared to that in the baseline) in Pakistan. In Mexico, Rivera et al. (2016) show that a carbon tax of US\$100/tCO_2 would cause total exports to drop by more than 2%.

It is argued in the literature that even if some countries introduce carbon tax unilaterally, it would not be as effective as it should be to reduce global GHG emissions because of emission leakage. Emission leakage occurs through two channels: (i) movement of emission intensive production from countries with more stringent environmental regulations to countries with none or less stringent environmental regulations and (ii) energy market channel (Fischer and Fox, 2012; Baylis et al. 2013; Aldy and Stavins, 2012; Arroyo-Currás et al. 2015). The potential of emission leakage through the first channel occurs when a carbon tax unilaterally imposed in a country or a region (i.e., group of countries), emission intensive firms (e.g., iron and still, cement) face higher costs due to increased energy prices. These industries would either tend to relocate the existing plants in countries and regions where 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. Emission 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.

Using a multiregional energy economy and climate policy model, Arroyo-Currás et al. (2015) examine emission leakage through cost-competitiveness and energy markets. Considering various scenarios, the study shows that up to 15% of the total emission reduction would leak from EU countries to the rest of the world (e.g., China, India, US, Middle East) when the EU 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% of emission reductions achieved through a unilateral carbon tax in the United States could leak elsewhere. Using a CGE model, Elliott et al. (2010) show that 20% of the emission reduction achieved in the industrialized countries through a carbon tax of US$29/t$CO_2$ would be offset by emission leakage to the developing countries. Using a simple two-sector, two-input general equilibrium model, Baylis et al. (2013) find that emission leakage could exceed the domestic emission reduction achieved by a unilateral carbon tax.

3.3 Carbon Tax vs. Cap and Trade Debate

The ongoing debate between carbon tax vs. cap & trade or emission trading system has created some confusion on the selection of these instruments. Several economies, including Canadian provinces of Ontario and Quebec, China, New Zealand, Republic of Korea, California and northeastern and mid-Atlantic states in the US have introduced ETS; Canadian province of Alberta and British Columbia, Colombia, Chile and Mexico have introduced carbon tax; and some members of European Union have introduced carbon tax and at the same time joined the EU-wide ETS (Timilsina, 2018). In an ideal situation, a carbon tax and cap & trade or emission trading system are equivalent in reducing CO_2 emissions and associated economic impacts. The difference between them rests in setting the emission price that is the actual instrument to cut CO_2 emissions. Emission prices are directly set by the policy makers under the carbon tax, whereas they are set by the market when emission reductions or limitations (or cap) are set by the policy makers (Hafstead et al. 2017). In the case of carbon tax, the emission price is known but emission reduction remains uncertain, whereas the reverse is true in the case of cap & trade.

In practice, these two policy instruments vary significantly due to their design architectures, such as quota allocation rules in the emission 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 carbon tax, other features unchanged; ETS would be different if emission allowances are distributed through grandfathering as ETS does not generate revenue to governments (Timilsina, 2018). A number of qualitative analysis have discussed the debate between the carbon tax and

ETS.[15] Chief among the analyses are Goulder and Schein (2013), Metcalf (2009a), Aldy (2017b) Aldy et al. (2017), Hafstead et al. (2017) and Aldy et al. (2008). Goulder and Schein (2013) clarify some of misconceptions regarding the superiority of carbon tax over ETS on the ground of sharing the burden between polluters (firms) and consumers or preserving international competitiveness and argues that there is no fundamental difference between carbon tax and ETS on these dimensions (i.e., burden sharing, competitiveness impacts) if the policies are designed properly. Aldy et al (2017), Aldy et al. (2017), Hafstead et al. (2017) contrast carbon tax and ETS in terms of uncertainties involves and make some suggestions to reduce the uncertainties.

Quantitative analyses measuring the difference in economic impacts between 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). Some of findings of this review on the key issues of carbon tax, such as economic impacts, distributional impacts, revenue recycling, competitiveness impacts, could be supported by analysis carried out for cap & trade system where initial emission allowances are distributed through auctioning.[16] Any difference in results between carbon tax and ETS, are not from the fact that they are different policy instruments, rather the different results are caused by the difference in their design architecture. Impacts of each policy would be significantly different when design features, such as revenue recycling schemes, are altered. It is, therefore, more appropriate to compare the same instrument (either carbon tax or ETS) under alternative design architectures than comparing carbon tax and ETS as such.

Some of the practical aspects that might have influenced policy makers to select cap & trade vs. carbon tax are highlighted in Timilsina (2018). If not differentiated across the sectors, fuels and introduced as uniformly throughout an economy, a carbon tax is easier to implement compared to ETS, because a uniform carbon tax does not require the complex monitoring and verification process, which is essential under the ETS. The complexity of ETS does not rest only

[15] Wirl (2012) and Karp et al. (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.

[16] For example, Parry and Williams (2010) examine the efficiency and equity issues of a cap & trade system and find that the cap & trade policy with auctioning all allowances and recycling the revenues to cut income taxes would be most efficient (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.

on the monitoring and verification of emission reduction, but also on initial allocation of emission allowance, which is always complex. The monitoring and verification of compliance of the allowances could be expensive not only due to high administrative cost, but also potential legal compliance cost. There is also a perceptional factor that matters, for example, being a 'tax' a carbon tax could be seen as a burden by industries and households, whereas ETS could be perceived as a new market opportunity and could be supported by industries (Timilsina, 2018).

4. Ways to Increase Political Appetite for the Carbon Tax

Although carbon tax is the most efficient instrument to reduce GHG emissions, it has not been widely introduced due to the reasons discussed in the preceding section. There are ways to reduce the impediments to carbon tax and increasing its political acceptance. This section discusses, based on in-depth research carried out by existing studies, how the resistance to carbon tax be lowered and its adoption can be enhanced. Some of the key strategies to increase the political appetite for carbon tax are finding the appropriate schemes to recycle carbon tax revenues to the economy so that adverse economic impacts of carbon tax can be reduced or eliminated and addressing the competitiveness loss.

4.1 Selecting the right revenue recycling schemes

One of the design schemes that lowers the economic costs of a carbon tax is an appropriate scheme to recycle carbon tax revenue to the economy. Since a carbon tax generates, depending upon the tax rate, a large amount of government revenue, recycling of this revenue also influences the economy significantly. A rich literature, both theoretical and empirical, is devoted in examining the revenue recycling effects of a carbon tax. There are several schemes considered in the literature to recycle carbon tax revenues to the economy. These include lump-sum transfer (or direct cash transfer) to households, using them to cut existing taxes (e.g., labor tax, capital tax, taxes on goods and services, corporate income tax), increasing public expenditure on infrastructure and welfare programs, subsidizing cleaner or green technologies.

The most common revenue recycling approaches discussed in the literature are: lump-sum transfer to households and cutting existing taxes. When compared with the no-recycling case, where government uses the increased tax revenue in the same way it does before the introduction of the carbon tax (e.g., public expenditure, government savings), recycling tax revenue to households as a lump-sum transfer reduces the economic cost of a carbon tax. Some of the studies presented in Table 1 provide evidence of this. For example, Mahmood and Marpaung (2014) show that a US$50/t$CO_2$ carbon tax would cause 2.3% 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% if the tax revenue is recycled to households as a lump-sum transfer. Similarly, Meng et al. (2013) show that a AS$23/t$CO_2$ carbon tax causes 0.59% GDP loss in Australia when tax revenue is not recycled, the GDP loss drops to 0.48% when the tax revenue is recycled to households through a lump-sum rebate.

Table 4 provides comparisons of revenue recycling schemes reported in various studies. It would also be possible to rank revenue recycling schemes in terms of their impacts on either GDP or welfare, although generalization of the ranking is difficult. The revenue recycling scheme that causes the lowest loss of GDP or welfare is considered the best. If a revenue recycling scheme causes an increase in welfare or GDP (see e.g., McKitrick, 1997; Jorgenson et al. 2015; McKibbin et al. 2015), it would be even better.

The cost of carbon tax would be lowered further if the tax revenue is recycled to cut existing taxes. Some studies presented in Table 1 show that economic costs of a carbon tax, measured either in terms of GDP loss or welfare loss, would be smaller when tax revenue is used for cutting existing taxes than recycling it to the households through a lump-sum rebate. For example, McKitrick (1997) shows that a carbon tax required to reduce a given amount of CO_2 emissions (12.5% from the baseline) in Canada, causes 0.8% GDP loss when the tax revenue is recycled to households through a lump-sum transfer. The loss drops to 0.5% and 0.3% when the tax revenue is recycled for cutting taxes on goods and services (GST) and personal income tax, respectively. Timilsina and Shrestha (2007) find that a carbon tax required to reduce 10% of CO_2 emission from the baseline in Thailand reduces economic welfare by 0.73% when tax revenue is recycled to households through a lump-sum transfer. The welfare loss drops slightly to 0.7% when the tax revenue is recycled to cut the labor tax and significantly to 0.05% when the tax revenue is recycled to cut indirect taxes on goods and services.

Table 4. Examples of studies examining carbon tax revenue recycling

Study	Revenue recycling scheme	Findings
Benavente (2016) – Chile; Allan et al. (2014) – Scotland; Mahmood and Marpaung (2014) – Pakistan; Meng et al. (2013) – Australia	No recycling (or used by the government for public expenditure) vs. lump-sum rebate to households	Transferring to household is better (less GDP loss) than not recycling the revenue (consumed by the government)
Timilsina and Shrestha (2002) – Thailand Goulder, 1998 (U.S.); Goulder et al. 1997 (U.S.); Parry, 1997 (U.S.) Orlov and Grethe, (2014) - Russia	Lump-sum rebate vs. income tax cuts	Recycling carbon tax revenue to cut income tax would be better than recycling it to households through a lump-sum rebate as the former causes lower welfare or GDP loss as compared to the latter
McKitrick (1997)	Revenue recycled to cut corporate income tax, lump-sum transfer to households, to cut taxes on goods and services and to cut personal income tax	Based on GNP impacts, recycling tax revenue to personal income tax would be the best option as it would increase GNP. The other revenue recycling schemes are ranked as follows (causing lowest GNP to highest): revenue used to cut taxes on goods and services, revenue recycled to households as lump-sum rebate and revenue used to cut corporate income tax rates
Alton et al. (2014)	Revenue is recycled, respectively for social transfer, cutting sales tax and cutting income tax	Based on GDP loss caused by the carbon tax, recycling tax revenue to income tax would be the best, followed by using tax revenue to cut sales tax and using it for social transfer to households
Jorgenson et al. (2015)	Revenue recycled to cut capital tax rate, capital and labor rates together, labor rate, government deficit and debt and recycling it to households as lump-sum rebate and used for government purchases	Based on GDP impacts caused by the carbon tax, recycling tax revenue to cut capital tax would be the best scheme as it causes GDP to increase in the long-run; the other revenue recycling schemes are ranked as follows (causing lowest to highest GDP loss): labor rate reduction, government purchases, deficit and debt reductions, and lump transfer to households
McKibbin et al. (2015) – U.S.	Revenue recycled to households as a lump-sum transfer and to cut, respectively, labor tax, capital tax and government deficit	Based on GDP impacts caused by the carbon tax, recycling tax revenue to cut capital tax would be the best revenue recycling scheme as it causes GDP to increase in the long-run; the other revenue recycling schemes are ranked as follows (causing lowest to highest GDP loss): revenue used to cut labor tax, revenue recycled to households as a lump-sum rebate and revenue used to cut government budget deficit
Tuladhar et al. (2015) – U.S.	Revenue recycled to households as a lump-sum transfer and to cut, respectively, labor tax, capital tax and government deficit	Based on welfare impacts, the revenue recycling schemes are ranked as follows (causing lowest to highest welfare loss): revenue used to cut corporate tax, revenue used to cut personal income tax, revenue recycled to cut government budget deficit and

		revenue recycled to households as a lump-sum rebate
Liang and Wei (2012) - China	Revenue recycled to cut indirect tax and transfer to rural households	Revenue recycled to cut indirect tax reduces economic loss and increased transfer to rural households decrease urban-rural income inequality

Several studies (Goulder, 1998; Goulder et al. 1997; Parry, 1997) provide elaborative explanations 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 elaborated this issue. These studies suggest that when a carbon tax is introduced to an economy where existing taxes, such as income taxes, have already created distortions in the factor markets, the carbon tax further exacerbates the distortions. This effect is called 'tax interaction' effects. 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) highlights two points in this regard: how much cost of an environmental tax could be offset by recycling the carbon tax revenue to cut factor tax rates and how much inaccuracies or errors are introduced in the estimation of the cost of a carbon tax if the pre-existing distortions are ignored. They suggest that the efficiency gain from recycling revenues to cut factor taxes instead of transferring it to the households as a lump-sum rebate is equal to the amount of recycled revenue times the marginal excess burden of taxation.

A few studies also report positive impacts on GDP for selected schemes of revenue recycling. For example, McKitrick (1997) show an increase in GDP for a hypothetical carbon tax in Canada when the tax revenue is recycled to households through a payroll tax cut. McKibbin et al. (2015) find increased GDP and employment from a carbon tax in the long run if the carbon tax revenue is used to cut capital taxes. They found that the cut in capital tax raised investment, employment and wages.

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 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 Colombia, carbon tax revenues will be recycled to accelerate deployment of innovative clean technologies to reduce GHG emissions (World Bank, Ecofys and Vivid Economics, 2017). 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 electricity generation, efficiency improvements of energy utilizing technologies, does not lower the economic costs of carbon tax. Instead it would 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), exacerbating the economic distortions. Timilsina et al. (2011) find that if part of the revenues from a carbon tax on fossil fuels is used to subsidize biofuels, it significantly helps expand the latter, but also causes additional GDP loss on top of what carbon tax has already caused. 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. Using a CGE model, Verde and Pazienza (2016) find that the revenue of carbon tax imposed to non-ETS sectors would be less costly than an electricity surcharge to subsidize renewable energy in Italy. Galinato and Yoder (2010) examine a scheme where energy sources with high emissions to energy price ratio are taxed and the tax revenue is used to subsidize sources with low emissions to energy price ratios. The study finds that the tax/subsidy program would increase the welfare as compared to a no-tax scenario. If the subsidies for low-emitting energy sources are funded through general tax instead of the emission tax it would cause further welfare loss.

Some existing literature considers recycling carbon tax revenue to industries either through production subsidies or cuts in corporate tax rates or cutting indirect tax rates. Analyzing the impacts of a carbon tax under alternative revenue recycling schemes in South Africa, van Heerden et al. (2016) find that recycling carbon tax to cut VAT rates would be more economical (causes lower GDP loss) than when the revenue is used to subsidize green energy. However, if the VAT rate cut would be the most efficient option to recycle carbon tax revenue in South Africa cannot be confirmed as the study does not consider many other possible revenue recycling schemes such as cutting income taxes. Using a recursive dynamic CGE model of China, Liang and Wei (2012) find using a part of carbon tax revenue to reduce indirect tax and the remaining part to transfer to households would reduce the economic cost of carbon tax; it also contributes to reduce rural-urban income inequality. Similar finding for China is also reported by Lu et al. (2010).

Some studies also consider using carbon tax revenue to reduce debt (Jorgenson et al. 2015; McKibbin et al. 2015; Tuladhar et al. 2015). The results in these studies are different for the same tax rate of US$15/t$CO_2$. Jorgenson et al. (2015) and Tuladhar et al. (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. All three studies, however, show that recycling carbon tax revenue to cut labor or capital tax would be better as compared to recycling it to households as a lump-sum transfer or using it to cut the government deficit.

4.2 Addressing Competitiveness Loss and Emission Leakage

Since loss of competitiveness of energy intensive trade exposed 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 which do not contribute to global efforts to combat climate change by introducing an efficient policy, such as carbon tax. This type of tax on imports is commonly known as 'border tax adjustment' or 'BTA' in the literature (Clarke, 2010; Lockwood and Whalley, 2010; Elliott et al. 2010). A BTA refers to introduction of a tax on imports of goods and services in proportion to their carbon footprints so that the exporting country is forced to cut CO_2 emissions indirectly (through reduction of exports). A large literature investigates the impacts of BTA (see, e.g., Gentry, 2017; Tang et al. 2015; Keen and Kotsogiannis, 2014; Mattoo et al. 2013; Burniaux et al. 2013; Li et al. 2013; Li et al. 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.

Several studies have analyzed impacts of BTAs and reported the impacts of BTAs. However, the results and conclusions are significantly different across the studies. For example, using a global CGE model to analyze the economic effects of BTAs, Burniaux et al. (2013) find that economic impacts are small, and vary depending on how BTAs are implemented. Dong and

Whalley (2012a) also report small impacts of carbon motivated BTA using a global CGE model. Similarly, using a recursive dynamic CGE model, Tang et al. (2015) show that a BTA tax imposed by the rest of the world to Chinese imports at the rate of US$20, US$60, and US$100 per ton of carbon would cause China's total exports to drop by 0.021%, 0.062%, and 0.103%, respectively.

Other studies, such as Matto et al. (2013), argue that BTAs could be highly damaging to developing countries' international trade. Matto et al. (2013) find, using a recursive global dynamic CGE model, if a BTA exercised by developed countries is based on the carbon content of imports, it would increase average tariffs on merchandise imports from India and China of over 20% thereby depressing their manufacturing exports 16% to 21%. On the other hand, if the BTA is based on the carbon content in domestic production, it would inflict less damage on developing country trade.

The study suggests that any international agreement on trade actions should be pursued under the climate change negotiation rather than leaving it for future negotiations in the WTO. While comparing the economic impacts of a domestic carbon tax in South Africa vs. a BTA that could be imposed if the country does not implement a domestic carbon tax, Alton et al. (2014) show that a US$30/tCO2 domestic carbon tax would achieve the national emissions reductions targets set for 2025 with 1.2% welfare loss. On the other hand, if trading partners unilaterally impose a carbon consumption tax on South African exports, the welfare would be higher than that from domestic carbon tax.

The second option to address the competitiveness loss of a sector is to compensate the sector through various measures (Bohringer et al. 2017a, Bohringer et al. 2017b; Gray and Metcalf, 2017; Metcalf, 2014). Some of them are: (i) general cuts in payroll and corporate income taxes of energy intensive and trade exposed (EITE) industries, (ii) providing corporate income tax credits tied to carbon tax payments of EITE industries, (iii) providing disproportionate relief indirectly to EITE sectors whereby carbon tax revenue is used to lower the top corporate income tax rate (Metcalf, 2014). No consensus however exists on which compensating measure would be the best from environmental and economic grounds. The selection of the compensating measures depends on multiple factors such as level of unilateral carbon tax in a country, structure of international trade of this country, level and types of existing taxes influencing domestic production and international trade, etc.

Gray and Metcalf (2017) examine the possibility of utilizing carbon tax revenues to address competitiveness concerns. They find that a system of carbon credits tied to carbon tax payments could provide some compensation to EITE sectors. They also show that output based tax credits are likely to create better incentives for firms than allowing a deduction on the corporate income tax for carbon tax payments because the latter reduces the marginal incentive of the carbon tax by the corporate income tax rate — more than one-third.

Bohringer (2017a) develops a theoretical model and numerically solves it using Canadian and U.S. data to examine the efficacy of a measure, output based rebate (OBR), to address the competitiveness loss due to a carbon tax. It finds that if the larger country (here US) does not have a carbon tax and smaller country (here Canada) introduces one, the OBR rates needed to compensate its EITE firms in Canada to keep at the level before the carbon tax, would be insensitive to the U.S. carbon policies. On the other hand, the Canadian OBR rates drop by almost 50% if the U.S. also imposes an equally high carbon tax as in Canada. Bohringer (2017b) further investigates the effectiveness of the OBR scheme by employing a stylized CGE model calibrated with world economy data (GTAP database). The study shows that a compensating measure that combines output-based rebating to production of EITE goods with a consumption tax on all use of the same EITE goods would be better (welfare improving from a situation in the absence of any compensating mechanism). The study also argues that since this mechanism is equivalent to full border carbon adjustment in certain conditions (i.e., carbon tariffs and export rebate are not differentiated across importers), this strategy would be more practical than the border carbon adjustment because the latter is politically contentious under existing WTO rules.

4.3 Distributional Impacts of the Carbon Tax

One of the key concerns in relation to carbon tax is its potential regressive impacts, meaning that it disproportionately impacts poor households[17] (Williams et al. 2015; Mathur and

[17] In the distributional analysis of carbon tax, where change 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).

Morris, 2014; Verde and Tol, 2009; Callan et al. 2009; Baranzini et al. 2000). This is because carbon tax increases energy prices and poor income households have relatively a higher expenditure share on energy consumption (Fullerton et al. 2012; Marron and Toder, 2014; Callan et al. 2009). Existing studies analyzing the distributional impacts of carbon tax concur that the regressivity of a carbon tax can be reduced by transferring the carbon tax revenue to low income households (Callan et al. 2009; Verde and Tol, 2009; Gonzalez, 2012; Jiang and Shao, 2014; Renner, 2018).

Studying the effects of carbon tax and revenue recycling across the households differentiated by income in Ireland, Callan et al. (2009) find higher costs of carbon tax on low income households as compared to the high-income households[18]; however, if the carbon tax revenue is transferred more to poor households through increased social benefits and tax credits, the regressive impacts of carbon tax on poor households can be offset. Callan et al.'s findings, however, need to be interpreted carefully because the model they used is not a general equilibrium model, their methodology does not account for many indirect effects. For example, a carbon tax causes the national economy to shrink thereby causing lower sectoral outputs and lower wage rate. Moreover, it could reduce government expenditure on public goods. While, the direct transfer of carbon tax revenue to the poor households could increase their welfare, it could depress the economy in the longer run and ultimately might impact the low-income households. The same study (Callan et al. 2009) was further extended by Verde and Tol (2009) using an input-output approach and found slightly different quantitative results with same conclusion. Yet, the issue raised above (i.e., the trade-off between the short-term welfare gain in the low-income households and long-term overall economic loss) is not resolved. Similar findings (i.e., if carbon tax revenue is recycled to low income households, the carbon tax would be progressive instead of regressive) are also reported in Renner (2018) and Gonzalez (2012) for Mexico. Gonzalez's results also hold true for U.S. data. Jiang and Shao (2014) also report similar findings for Shanghai, China. The problem here again is with the methodology. While Renner (2018) and Jiang and Shao (2014) use input-output models, Gonzalez (2012) uses a static CGE model. For the reason explained earlier, an input-output model is not a credible tool to analyze the

[18] A €20/tCO_2 carbon tax costs the poorest and richest households €3 and €4 per week, respectively. Note that average income of the poor households is much lower as compared to rich households.

distributional impacts of a carbon tax. A static CGE model too cannot simulate the trade-off between current welfare gain in low income households and overall economic loss in the future caused by a carbon tax.

As discussed above, the impacts of carbon tax on the 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 carbon tax. Low income households would benefit more when carbon tax revenue is recycled as a lump-sum rebate than used to cut existing tax. Using an input-output model of the U.S. economy, Mathur and Morris (2014) show that even if only11% of the carbon tax revenue is transferred to the poorest two deciles of households, their welfare would increase. On the other hand, if the carbon tax revenue is used to cut existing taxes, it is the higher income households who benefit (i.e., their welfare loss due to the carbon tax decreases). Low income households still face higher welfare loss as before. Williams et al. (2015) examine the carbon tax efficiency (i.e., economic or welfare cost) and regressivity using a dynamic overlapping-generation[19] and micro-simulation models of the United States. It shows that an average (or 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. On the other hand, if the households are split by their income, 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 welfare of low income households from the baseline or higher reduction of welfare loss as compared to that of high income households). However, although the CGE model was an intertemporal one, the microsimulation model used for assessing distributional impacts was not capable to measure the impacts in the long-term. Therefore, the study could not confirm if the progressiveness of the carbon when tax revenue is recycled to households in a lump-sum manner holds in the long-run. Their conclusion is recycling revenue to cut capital tax makes a carbon tax most efficient but exacerbates its regressivity. On the other hand, recycling the revenue as a lump-sum rebate is less efficient, but would be more progressive. Williams et al. (2014) examine distributional

[19] The intertemporal dynamic overlapping generation CGE model used in Williams et al. (2017) allows a representative household agent for a generation to make decisions on its lifecycle consumption and savings for its 55-year economic lifetime, from entry into the labor force until death.

effects of a carbon tax across income groups as well as across geography and conclude that geographic differences in carbon tax incidence are mainly influenced by differences in sources of income. They find that recycling tax revenue to cut capital taxes disproportionately benefits states with large shares of capital income; recycling the tax revenue to households through a lump-sum rebate favors relatively low-income states; and recycling the tax revenue to cut labor taxes evenly distributes the costs of a carbon tax across states. The geographic differences in carbon tax incidences are however substantially smaller as compared to that across income groups. Other studies, such as Klenert and Mattauch (2016) Mathur and Morris (2014) also have similar findings like that in Williams et al. -- a carbon tax with lump-sum revenue recycling would be progressive in terms of its distributional effects.

In British Columbia, Canada, where carbon tax has been introduced since 2008 and carbon tax revenue is being used to cut existing tax rates, rural households in Northern British Columbia, 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% of carbon tax revenue to transfer to eligible households. Using a CGE model of Canada, Beck et al. (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, using a general equilibrium model, these effects caused through commodity prices vs. factor prices and show that a carbon tax's impacts on factor and commodity prices have opposing effects on inequality. Inequality drops due to the impacts of carbon tax on factor prices, the reverse would be true due to the impacts of carbon tax on commodity prices. Their conclusion is that carbon tax has a U-shaped (non-monotonic) relationship with inequality.

Some economists argue that carbon tax could be used to finance global infrastructure and inequality gaps (Jakob et al. 2016; Davies et al. 2014). Analyzing a scenario that considers limiting global warming to below 2 degrees Celsius, 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, infrastructure access could be further expanded in developing countries. Using Nordhaus's RICE model, Davies et al. (2014) estimates that a 100-year global carbon tax path for the 2015-2115 period needed to stabilize global emissions such that temperature does not rise 2° C above the preindustrial level before 2105, can generate enough revenues to improve the global Gini coefficient by 3% and to raise the income share of the bottom decile by 81% on average from 2015 to 2105 if the revenue is distributed across countries on a per capita income basis. The central issue is however whether such a proposition would be politically palatable.

4.4 Highlighting the Co-benefits of the Carbon Tax[20]

A carbon tax does not only reduce CO_2 emissions, it also reduces all other pollutants caused by burning of fossil fuels, such as particulate matters, oxides of sulfur and nitrogen, which cause serious challenge to human health. Reduction of local air pollution with serious human health impacts 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 carbon tax. It considers various scenarios for carbon tax rates to achieve 3 to 5% annual reduction of energy intensity between 2015 and 2030. A carbon tax rate of US$72/t$CO_2$ (2007 price) would be needed by 2030 to reduce CO_2 intensity 4% annually. The carbon tax would reduce 24% of national CO_2 emissions by 2030 from the baseline (or no carbon tax scenario). It would reduce SO_2 and NO_x emissions in 2030 by 25% and 19%, respectively from the baseline. National population weighted annual average PM2.5 concentration in 2030 drops by 12% from the baseline. The reduction of PM concentration would avoid 94,000 premature mortalities, which are more than the estimated number for the US Clean Power Plan in 2030. Using the international estimates for health valuation, the value of health co-benefits are 3.7 times larger

[20] 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 are specifically health benefits (or co-benefits) of carbon tax policy.

than 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.

Parry et al. (2015a) estimate the health co-benefits of a carbon tax in the largest 20 emitting countries through the reduction of local air pollution. Countries which can benefit the most using the carbon tax to reduce local air pollution are: Saudi Arabia, the Islamic Republic of Iran, Russia, China, 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 carbon tax to reap the associated health benefits.

An earlier study, Li (2006) finds high local air pollution benefits of carbon tax in Thailand. It shows that if the feedback from improved heath achieved through reduction of local air pollution is accounted for, a carbon tax, which normally reduces GDP, would increase the GDP and reduce the welfare loss. A carbon tax that reduces GDP by 1% without including the health co-benefits, increases it by 4% when the co-benefits are taken into account. It would decrease the welfare impacts of carbon tax by a half.

4.5 Communicating the Carbon Tax to Policy Makers and the General Public

Governments or policy makers who are reluctant to introduce a carbon tax often argue that the general public does not like a carbon tax. Some governments do not show interest to carbon tax because of a perceptive threat of losing power or the next election. Some studies have investigated public perception towards a carbon tax policy. 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 initially with a perception that the carbon tax would impose a huge burden on them, their opposition may not sustain once they are well informed about the pros and cons of the carbon tax. Using polling data, Murray and Rivers (2015) show that the majority of the public was opposed when the carbon tax was introduced in British Columbia, Canada for the first time in 2008, but that three years post-implementation, the public generally supported the carbon tax. Gevrek and Uyduranoglu (2015) conduct a choice experiment in Turkey to assess public preference to carbon tax and show that Turkish people prefer a carbon tax if it is designed with a progressive cost distribution instead of regressive cost distribution.

Baranzini and Carattini (2017) assess public acceptability of carbon taxes in Geneva, Switzerland using survey data and find that individuals are more concerned by the environmental effectiveness of the tax than its economic costs. They find that people are interested in receiving more local environmental benefits from a carbon tax. They do not worry about the competitiveness issues but express concerns on its distributional effects. The study concludes that effective communications, particularly explaining to the people of 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 level of environmental awareness of the Swiss population is much higher than that in many developing countries.

Public communications and debates were exercised in most countries where 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). Evidence suggests that a long public debate occurred before the introduction of carbon pricing, including carbon tax in many countries. In Canada, a long public debate ensued (Harrison, 2012) before the Prime Minister Justin Trudeau's Liberal Government introduced the federal carbon tax. In South Africa, the government's assessment (through studies, consultations) and public debate on carbon tax started in 2010 almost a decade in advance of the implementation of carbon tax. China piloted seven city level emission trading schemes, before it finally introduced a national emission trading scheme in November 2017. Years of public debate took place in British Columbia on the selection of carbon mitigation policies although then Provincial Premier Gordon Campbell's carbon tax introduction came as a surprise in 2008 (Harrison, 2012).

5. Carbon Tax in Practice

Despite the extensive research on carbon tax, implementation of carbon tax in practice is limited for the reasons we discussed earlier. However, policy makers' perception towards it is changing and its implementation in recent years has increased. This section discusses carbon taxes already introduced in practice and some international initiatives to facilitate the implementation. This section also shows how the ongoing research has helped in the design of existing carbon tax systems.

5.1 Existing national carbon taxes

As of January 1, 2018, more than 20 economies have already introduced carbon tax around the world. Table 5 briefly summarizes the attributes of these taxes. Nordic countries introduced carbon tax in the early 1990s and currently their carbon tax rates are the highest in the world (e.g., US\$27/tCO_2 in Denmark to US\$140/tCO_2 in Sweden). 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, Ecofys and Vivid Economics, 2017).

Although 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 carbon tax in practice often is constrained by political factors and does not follow the optimal routes suggested by theory. Considering the political appetite and acceptability to consumers, all economies that have introduced carbon tax 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, Canada, when 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 at CN\$30/tCO_2, since than it has remained constant (Rivers and Schaufele, 2015). When the carbon tax was introduced for the first time in January 1991 in Sweden, the rate was US\$40/tCO_2 at the time on coal, natural gas and petroleum products; industrial users paid half of the rate, and certain energy intensive industries, horticulture, mining, manufacturing and pulp and paper, were completely exempted from the carbon tax (IEA, 2008). Currently, the Swedish carbon tax rate reached US\$140/tCO_2 (i.e., more than three times higher than the initial rate); however most energy intensive sectors (e.g., power plants, domestic aviation, petroleum refineries, manufacturing industries) are covered by the Emission Trading scheme of the European Union (EU-ETS) and therefore are exempted from the domestic carbon tax. Recently, three Latin American countries, Chile, Colombia and Mexico have introduced carbon tax. They have started with a small rate US\$3.21/tCO_2 in Mexico and

US$5/t$CO_2$ in Chile and Colombia. Chile's carbon tax is applied for the electricity sector only and biomass is used for electricity generation, whereas Mexico's carbon tax covers all sectors, but it excludes natural gas, the country's main fossil fuel source, from carbon taxation for gaining the public acceptability of the carbon tax (Narassimhan et al. 2017). In Colombia, the carbon tax on natural gas covers only the petrochemical and refinery sectors.

Table 5. Existing national carbon tax

Economy	Year of Introduction	Tax Rate (2017 US$/t$CO_2$)	Remarks
Finland	1990	69-73	Peat and natural gas pay lower rates, wood industry is exempted
Sweden	1991	140	Industries covered by EU-ETS are exempted
Norway	1991	3-56	It varies across activities, sectors and fuels (higher tax on gasoline, lower tax on diesel; natural gas face higher tax than coal)
Denmark	1992	27	
United Kingdom	1993	24	
Latvia	1995	5	
Slovenia	1996	20	
Estonia	2000	2	
Switzerland	2008	87	
Ireland	2010	24	
Iceland	2010	12	
British Columbia, Canada	2008	24	Covers all fossil fuels, and also biodiesel
Alberta, Canada	2017	16	Fossil fuels for transportation and heating
Ukraine	2011	0.02	
Japan	2012	3	
France	2014	36	Sectors not covered by EU-ETS
Mexico	2014	1-3	Natural gas is exempted from the carbon tax
Chile	2014	5	Only for stationary sources (turbines or boilers above 50 MWth)
Portugal	2015	8	
Colombia	2017	5	Carbon tax on natural gas covers only the petrochemical and refinery sectors.

Note: European countries which have joined the EU-ETS program exempt sectors covered by the EU-ETS from domestic carbon taxes.

Source: World Bank, Ecofys and Vivid Economics (2017)

The carbon tax revenue schemes vary across countries where carbon tax has been already introduced. Some countries or 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% of the 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 used for education and social programs.

Several countries are planning to introduce carbon taxes in the near future. In South Africa, a draft bill on national carbon tax has been on the table of Parliament since 2015, however, its introduction has been postponed several times. It is possible that government will finally introduce it in 2018.[21] The Canadian federal government proposed a federal carbon tax in 2016 requiring all provinces and territories to have a carbon pricing initiative by 2018 (World Bank, Ecofys and Vivid Economics, 2017).

Although carbon tax has been in practice for over the last 28 years in some countries (e.g., Nordic countries), it is gaining international attention more recently, particularly after the 2015 Paris Accord. Politicians who were reluctant to consider carbon tax due to potential resistance from the consumers or adverse implications to their voter base, started to take the challenge of discussing carbon tax and ultimately introducing it. The large pool of knowledge on various issues of carbon taxation and effective communication to policy makers of the fact that carbon tax is the most efficient policy instrument to mitigate climate change might have contributed to gradually increasing political acceptability to carbon tax. Many countries have identified carbon pricing, including carbon tax, as an instrument to achieve their Nationally Determined Contributions (NDC) under the Paris Accord. At the international level, more than 80 countries of the total 155 countries who are signatories to the Paris Agreement are considering using carbon pricing as a tool to meet their climate change mitigation goals specified in their NDCs. It was estimated that the total value GHG emissions mitigated through the carbon pricing instruments (both emission trading and carbon tax) in 2017 was US$52 billion (World Bank, Ecofys and Vivid Economics, 2017).

[21] The South African, February 2, 2018. https://www.thesouthafrican.com/carbon-tax-sa-budget-speech-2018/

5.2 International initiatives on the carbon tax

At the international level various initiatives have been launched to support and promote the use of carbon pricing including carbon tax. In 2014, during the UN Climate Summit in September, a Carbon Pricing Leadership Coalition (CLPC) was launched with the support of 74 countries and more than 1,000 companies.[22] The CLPC is a voluntary partnership of governments (national as well as sub-national), corporations and civil society organizations to advocate global carbon pricing through (i) strengthening carbon pricing policies to redirect investment towards addressing the climate challenge, (ii) enhancing the implementation of existing carbon pricing policies and (iii) to strengthen cooperation on knowledge and information sharing on carbon pricing. The Coalition is expected to facilitate initiatives in development and implementation of carbon pricing policies by various economic agents (i.e., government, business). In 2015, World Bank President Jim Yong Kim and IMF Managing Director Christine Lagarde initiated a 'Carbon Pricing Panel' with heads of government and private sector leaders to provide political momentum and to complement the voices of government and industry leaders in the CPLC.

At the 21st Conference of Parties to the UNFCCC, held in Paris in December 2015, where the Paris Climate Accord was endorsed, New Zealand led a Ministerial Declaration on carbon pricing.[23] Nineteen countries (Australia, Canada, Chile, Colombia, Germany, Iceland, Indonesia, Italy, Japan, Mexico, Netherlands, New Zealand, Panama, Papua New Guinea, Republic of Korea, Senegal, Ukraine, United States of America and United Kingdom) endorsed the declaration. This Declaration reflects countries' willingness to work together for developing standards and guidelines for using carbon pricing instruments. Most of these countries have already introduced either carbon tax or emission trading or both schemes to reduce their GHG emissions.

High level advocacy and awareness activities at the international level to promote carbon pricing, including carbon tax, is on rise. During the signing ceremony in New York of the Paris Agreement, six Heads of States, including Prime Ministers of Canada and Ethiopia, Presidents of

[22] Please visit http://www.carbonpricingleadership.org/ for more information on CLPC.
[23] New Zealand Ministry of Environment. http://www.mfe.govt.nz/news-events/ministerial-declaration-carbon-markets.

Chile, France and Mexico, the German Chancellor together with World Bank Group President, IMF Managing Director, California Governor, Rio de Janeiro Mayor and OECD Secretary-General urged the world to expand carbon pricing to cover 25% of global emissions by 2020, which is double the 2016 level and to further expand it cover 50% of global emissions within the next decade.[24]

6. Knowledge Gap

Since a large number of studies have been carried out covering many issues related to carbon tax over the last 30 years, no lack of knowledge exists on major issues of carbon tax, such as economic impacts of carbon tax, revenue recycling schemes, distributional impacts, competitiveness impacts and border tax adjustments. However, a knowledge gap still exists on some specific issues, such as equity vs. efficiency considerations while designing revenue recycling schemes; economic and distributional consequences of carbon tax which have been already in practice or under consideration and are politically desirable but economically inefficient. Some of these knowledge gaps are highlighted below.

Efficiency vs. equity of revenue recycling schemes. Based on a large number of studies, a general conclusion can be drawn that using carbon tax revenue for cutting existing distortionary taxes, particularly, income tax and indirect taxes would be more efficient economically (i.e., GDP/welfare gain or smaller GDP/welfare loss) as compared to not recycling the revenue (i.e., use for government expenditure) or recycling it to households through a lump-sum transfer. On the other hand, recycling the carbon tax revenue as a lump-sum rebate could make a carbon tax progressive as it helps low income households to receive higher welfare as 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 emission due to the carbon tax and further reduction of emissions due to financing clean and energy efficient technologies). This scheme is, however, economically

[24] "Leaders Set Landmark Global Goals for Pricing Carbon Pollution", World Bank Press Release, New York, April 21, 2016. http://www.worldbank.org/en/news/press-release/2016/04/21/leaders-set-landmark-global-goals-for-pricing-carbon-pollution

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 revenue to transfer to poor households (instead of all households), a part for cutting existing distortionary taxes, a part for subsidizing clean energy. Studies are lacking investigating a portfolio of revenue recycling schemes despite the fact that existing carbon taxes in practice have used the carbon tax revenues for multiple purposes (please see Section 5.1 above). For example, in British Columbia, Canada, carbon tax revenues were solely used to swap existing taxes. Later, when northern rural residents protested, the government started to transfer a part of the tax revenue to northern low-income households through a social program (Beck et al. 2016n). It is, therefore, important to investigate efficiency and equity of carbon tax revenue recycling schemes when carbon tax revenue is recycled for multiple purposes. Since different countries have different economic structures and social needs, the results from a study carried out for a country may not be applicable for other country. Thus, country specific studies on this topic are warranted.

Rationales of sectoral and fuel exemption of carbon tax. Studies are also missing to analyze key issues related to carbon tax in practice. For example, sectoral exemption (i.e., not to impose carbon tax to certain fuels or sectors) is a common practice in countries which have already introduced carbon tax. Theoretically, it is well established that such a sectoral exemption would be inefficient in terms of the environmental and economic impacts of a carbon tax. To achieve a given level of GHG mitigation a carbon tax with a wider base (no sectoral or fuel exemption) would be less costly as compared to that with a narrow base (sectoral or fuel exemption). However, few studies are available to measure the magnitude of economic and environmental impacts under different levels of exemption. Moreover, the empirical results could be different across the economies depending on their economic and international trade structures. Therefore, it would be important to assess the impacts of sectoral and fuel exemptions of a carbon tax. The results would help countries to decide whether or not to adopt an exemption to a carbon tax for a sector or fuel. What if the sector or fuel considered for tax exemption due to competitiveness or welfare concerns would be compensated through revenue recycling instead of exempted in the first place?

Analysis of carbon tax on full social cost basis. A common limitation of most studies assessing the cost of carbon tax is ignorance of costs other than pure economic costs. First, hardly any study has accounted for the benefits of climate change mitigation. It is understandable why climate change benefits are ignored when an analysis is carried out for a single country, especially a single developing country whose contribution to the global GHG emission is small. But climate change benefits have been ignored in most countries including large emitting countries or regions. Even global carbon tax studies ignore the reduction of climate change damages. Another rationale offered not to include the climate change benefits is the complexity of quantifying such benefits due to the scale of uncertainties involved with it. Most of studies have not included other environmental benefits, such local air pollution mitigation benefits, associated with a carbon tax for the same reason as stated above, complexity in quantification and uncertainties. Recently, some studies (e.g., Li et al. 2018; Parry et al. 2015a; Parry et al. 2014; Parry, 2012) have measured and highlighted the local environmental benefits of a carbon tax and argued that a carbon tax could be justified based on its local air pollution mitigation benefits alone. If both climate change mitigation benefits and local environmental benefits are accounted, a carbon tax could generate overall net social benefits. However, knowledge in this area is highly limited and more studies are needed. Rigorous analyses and effective communication of the results could significantly enhance the political and public acceptance of the carbon tax policy.

Overlapping of other climate policies with carbon tax. Some studies (e.g., Zakeri et al. 2015; Goulder and Schein, 2013; Levin et al (2011); Murphy and Jaccard, 2011; McKibbin et al. 2011; Metcalf ,2009a; Aldy et al. 2008; Grimaud and Lafforgue, 2008; Green, 2008; Gerlagh and van der Zwaan, 2006) have compared carbon tax with other policies to mitigate climate change, such as cap and trade scheme, mandates to clean and renewable energy, research and development on clean technologies etc. In EU countries, for example, several policies (e.g., carbon tax, emission trading, renewable energy mandates, etc.) are overlapping. Theoretically, when a carbon tax is introduced, other climate policies may not be needed; some of them would be automatically triggered. For example, if adequate level of carbon tax is introduced, clean and renewable energy would be more competitive with fossil fuels and would be automatically implemented. However, the level of carbon tax needed for stimulating some policies (e.g., stimulating solar or wind) would be too high and could cause a deep economic loss. It would not be efficient to introduce a carbon tax to some sectors while exempting others. In such a situation, a mix of policy instruments might be needed. But, when multiple policies are introduced, some sectors get 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 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 on climate change policies.

Carbon tax, poverty and shared prosperity. Despite the very rich literature with hundreds of peer reviewed studies over the last 30 years on various topics related to carbon tax, one issue has not been investigated: how would carbon tax influence poverty and shared prosperity? Considering carbon tax's adverse economic impacts and disproportionate impacts on the welfare of low income households because of their high expenditure share on energy, one could expect carbon tax might exacerbate poverty. On the other hand, if carbon tax revenue is recycled to households below extreme poverty, it could significantly contribute eliminate extreme poverty. Moreover, proper recycling of carbon tax revenue could boost shared prosperity. However, no study has been done in this area. This is an important research gap to be filled.

7. Conclusions

Policy makers and other stakeholders (academics, industry, civic society) who are not much familiar with carbon tax and climate change mitigation policies might have a perception that carbon tax is an emerging area. However, this is not true. Carbon tax, perhaps, has the richest literature in the field of environmental economics. Hundreds of studies have been carried out over the last 30 years covering several topics related to carbon tax. In this paper, we attempted to trace all peer-reviewed journal articles on carbon tax published since the 1970s. We presented the evolution of carbon tax over time classifying the existing literature by topics they investigated and by methods used for the investigation.

The paper comes up with several findings with some interesting revelations. Carbon tax attracted many researchers in the 1990s when climate change negotiation took momentum with the establishment of the United Nations Framework Convention of Climate Change (UNFCCC) in 1992 and its Kyoto Protocol in 1997. Many studies in the 1990s used a theoretical approach to investigate carbon tax related questions. However, its more empirical studies, particularly those based on computable general equilibrium modeling, that dominate the carbon tax literature because of high heterogeneity on carbon tax impacts across countries, economic sectors and economic agents.

During 2001-2009, studies on carbon tax slowed down. This was the period when climate change negotiation was not taking a concrete direction with the major players (United States and Canada) either rejecting or withdrawing from the key milestone of climate change negotiation, the Kyoto Protocol. Carbon tax literature has reemerged after the Copenhagen climate conference in 2009 and the Paris Climate Accord in 2015. After the Paris Agreement, carbon tax has further gained momentum from the policy perspective as many middle and even low-income country governments, international development communities and the private sector are showing interest in carbon pricing including carbon tax.

The major carbon tax issues examined over the last 30 years are: (i) economic impacts of carbon on economic sectors, economic welfare, international trade, (ii) comparison of schemes to recycle carbon tax revenues to the economy, (iii) competitiveness concerns and measures to address specifically the border tax adjustment, (iv) distributional consequences of carbon tax, and (v) series of specific and sectoral issues. The methods used in the investigation were (i) theoretical approach, (ii) partial equilibrium approach, (iii) computable general equilibrium modeling, (iv) input-output modeling and (v) review or qualitative analysis. The majority of studies dealing with carbon tax issues have employed the computable general equilibrium model as an analytical tool.

Based on the findings of most studies assessing the economics of the carbon tax, it can be concluded that the carbon tax causes overall economic loss measured in terms of GDP or welfare. Almost all studies, however, have not accounted for the benefits of avoiding climate change damage for two reasons: complexity and uncertainties in estimating the benefits, and the benefits are globally shared and the fraction to be received by a country of concern would be too small. Estimated economic costs of a carbon tax generated by different studies for different countries cannot be compared for many reasons such as difference in analytical methodology, assumptions, differences in the design of carbon tax considered such as revenue recycling schemes. For a given tax rate and revenue recycling structure, the costs vary across economies depending on their energy supply systems, production structures and international trade structures.

A clear pattern is observed to rank the revenue recycling schemes on the grounds of efficiency (i.e., based on impacts on aggregate welfare or aggregated economic output, GDP) from most studies examining carbon tax revenue recycling schemes. Not recycling of carbon tax revenue (i.e., using it by the government in the same way it does for other tax revenues in the absence of the carbon tax) 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. It would be better further (lower reduction of welfare or economic output) if the carbon tax revenues are recycled to cut existing distortionary taxes (e.g., personal income tax cut, labor tax cuts). Existing literature shows that recycling the tax revenue to boost economic outputs through investments or corporate tax cuts or capital tax cuts would be the best. Some studies, particularly those conducted for the United States, find increase in welfare and economic output when the carbon tax revenue is recycled to cut capital tax rates. While many studies considered to use carbon tax revenues for promoting clean and renewable energy technologies by subsidizing them, such a revenue recycling is good from the environmental perspective, as it reduces emissions further; however, it would be economically inefficient, as it causes further welfare and GDP losses. If the environmental benefits are quantified and accounted for in the welfare or economic output (GDP) measure, this conclusion could alter. No carbon tax study, however, has done this to date.

The efficiency and equity aspects of carbon tax often counteract thereby placing the policy makers or carbon tax policy designers in an ambivalent situation. A carbon tax even with the most 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, as it benefits high-income households more than low-income households. 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.

Loss of competitiveness of energy intensive trade exposed (EITE) sectors is one of the key reasons for the resistance to carbon tax. Studies have proposed and analyzed several instruments to address this concern. These include cutting payroll and corporate income taxes in EITE industries, providing 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 unilateral carbon tax in a country, its structure of international trade, level and types of existing taxes influencing domestic production and international trade, etc.

Carbon tax has been introduced in practice in many countries. Scandinavian countries introduced carbon tax in the early 1990s followed by other EU countries and more recently (after the Paris Agreement) other countries (e.g., Chile, Colombia, Mexico) have introduced carbon tax. The tax rate varies widely across the countries, from US\$3/tCO_2 in Mexico to US\$140/tCO_2 in Sweden. Although the economic theory suggests a uniform carbon tax with wider base in terms of its coverage of fuels and economic sectors would be more efficient, the carbon taxes introduced in practice are highly distorted in terms of their exemption or differentiation across the sectors and fuels.

While a carbon tax was a topic of academic research until a few years back, it has attracted wider attention from policy makers, international development communities, private sectors more recently, particularly after the Paris Climate Agreement. More than 80 countries that signed the Paris Agreement are considering carbon pricing, including carbon tax as one of their main policy instruments to realize the emission reduction pledges they have made under the Paris Agreement. Initiatives led by Heads of States of many countries and leaders of big corporations and international development communities have been started to promote carbon pricing, including carbon tax, and urged the world to expand carbon pricing to cover 50% of global emissions by 2030.

Despite the rich literature accumulated through extensive research over the last 30 years covering various topics on carbon tax, there are still research gaps in several fronts, including efficiency vs. equity considerations of revenue recycling schemes; analysis of carbon tax from the social cost perspective including ancillary benefits, such as benefits from local air pollution reduction; addressing overlapping of other climate policies with carbon tax and implications of carbon tax on poverty alleviation and boosting shared prosperity.

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