REVENUE RECYCLING AND COST EFFECTIVE GHG ABATEMENT: AN EXPLORATORY ANALYSIS USING A GLOBAL MULTI-SECTOR MULTI-REGION CGE MODEL

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Received 17 August 2017

Revised 21 December 2017

Accepted 3 January 2018

Published 20 March 2018

Carbon pricing generates revenues which can be recycled back into the economy in different ways to help mitigate the economic cost of abatement. These include, lump-sum transfers to households; reducing existing distortionary taxes, such as income taxes on labor and capital; investment in technology funds leading to energy/emissions efficiency improvements; and/or infrastructure developments that help expedite the adoption of low or lower carbon-intensive technologies. In this paper, we undertake illustrative simulations to explore how different revenue recycling options influence the overall economic outcome in terms of broad macroeconomic indicators, such as Gross Domestic Product (GDP) or household welfare. Environment and Climate Change Canada's (ECCC) multi-sector, multi-region Computable General Equilibrium (CGE) model (EC-MSMR) is used to simulate various revenue recycling options. These simulations are undertaken for the U.S. economy. The main findings of the paper are: (i) using carbon revenue for a general income tax reduction or investment subsidy is more advantageous than a lump-sum transfer to U.S. consumers in terms of welfare or GDP; and (ii) using carbon revenue for a sector-based subsidy such as renewable energy is more disadvantageous than a lump-sum transfer to consumers. In terms of accumulated welfare effects, our results indicate that the best carbon revenue recycling option is the investment subsidy or capital income tax reduction in the longer horizon; labor tax reductions yield the best outcome in the shorter horizons.

Keywords: Carbon pricing; revenue recycling.

JEL Codes: Q52, Q54, Q58

1. Introduction

Greenhouse gas emissions including carbon dioxide (CO₂) emissions from economic activity cause negative externalities. Carbon pricing is a market mechanism used to

address these externalities. Carbon pricing can be either a carbon tax, or the price of emission permits (IPCC, 2014). By attaching a price to CO₂ emissions the external costs caused by these emissions, such as those related to climate change, are factored into every carbon-emitting activity by encouraging consumers or producers to reduce carbon emissions in an efficient way.

Carbon pricing also generates revenues which can be recycled back to the economy in different ways to help mitigate the economic cost of abatement. These includes, for example, lump-sum transfers to households; reducing existing distortionary taxes such as capital and personal income taxes; investment in technology funds supporting renewable energy technology deployment or leading to energy/emissions intensity improvements; and/or infrastructure development that helps expedite adoption of available low or lower carbon-intensive technologies. In this paper, we use a version of Environment and Climate Change Canada's (ECCC) multi-region, multi-sector Computable General Equilibrium model (EC-MSMR) to illustrate how alternative revenue recycling options influence the overall economic outcome in terms of broad macroeconomic indicators such as Gross Domestic Product (GDP) or household welfare under a carbon pricing policy. Simulations are undertaken for the U.S. economy as was decided by the EMF 32 Inter-model Comparison of US Greenhouse Gas Reduction Policy Options.

Economists almost universally agree that carbon pricing is the most efficient way to engage in emission abatement (Nordhaus, 2013; Weitzman, 2013; Stiglitz, 2010). The "Economists' Statement on Climate Change," signed by over 2500 economists in 1997 explicitly states: "The United States and other nations can most efficiently implement their climate policies through market mechanisms, such as carbon taxes or the auction of emissions permits" (Jones, 1997). Major international institutions also support the carbon-price commitment (World Bank, 2014; IMF, 2014). Now more and more countries or regions are considering adopting carbon pricing strategies, especially after the conclusion of the Paris Agreement in December of 2015. According to World Bank (2016), in 2016, about 40 nations, including seven out of the world's 10 largest economies, and more than 20 sub-national jurisdictions, are putting a price on emitted carbon emissions. On average, carbon pricing policies cover about half of the emissions in these jurisdictions, which translate into seven Gigatonnes of carbon dioxide equivalent (GtCO₂e) or about 13% of global greenhouse gas (GHG) emissions.

Carbon pricing can generate fiscal revenue. According to the World Bank (2016), in 2015, carbon pricing initiatives generated about US\$26 billion for world governments, a 60% increase compared to the revenues raised in 2014, about US\$16 billion. In 2016, total carbon pricing revenue totalled almost US\$50 billion. This revenue can be recycled back to economies in revenue neutral ways to reduce existing distortionary taxes and/or address market failures that prevent the creation and adoption of energy/emissions efficient technology, thereby opening up the opportunity to reduce abatement costs.

There is increasing literature in this field, showing that the manner in which revenue from carbon pricing is recycled can make a difference in reducing abatement costs.

Gaskins and Weyant (1993) compare the results of the study on the macroeconomic costs of reducing U.S. CO₂ emissions by up to 30% by 2010 based on 1990 levels. In this study, the 14 participating modeling teams used lump-sum payments to consumers as the means of recycling the carbon tax revenues, while four participants also considered using the revenues to reduce distortionary taxes. They find that when the revenues were used to reduce distortionary taxes, the resulting abatement costs can be reduced substantially, by 35% to even 100%, particularly if the taxes on capital formation are reduced. The size of gains (or cost reduction) from revenue recycling would depend on the nature and magnitude of distortions. Appropriate structural parametrization of model is important for a comprehensive analysis on this issue (Piketty *et al.*, 2014; Saez *et al.*, 2012).

From a Canadian perspective, Peters *et al.* (2010) show that returning the revenue from auctioned permits back to the economy via tax cuts — either of federal or provincial personal income tax or business taxes — can reduce the abatement cost for Canada compared with intensity-based cap and trade systems. Landa *et al.* (2015) find that the revenues from the removal of energy subsidies and carbon tax collection redistributed through a reduction of the income tax for households and payroll tax for business sectors can bring about double dividend for Mexico. This is beneficial both in terms of GDP growth and CO₂ emissions reductions. Goulder (1995) finds that over the long run the U.S. abatement cost in terms of GDP loss as a result of a carbon tax of \$25/tCO₂ is reduced by 40–55% when the carbon revenues are recycled to reduce marginal rates of personal income tax rather than lump sum transfers. The IPCC Third Assessment Report (2001) finds that there are many instances of reduced GHG abatement costs; for example, in terms of welfare change, if GHG tax revenues are recycled through reductions in employment taxes, welfare loss is reduced, especially in Europe.

Recycling carbon revenue back to economy opens up an opportunity to restructure the taxation system. So searching for optimum way of recycling carbon revenue should be a part of optimum taxation scheme. Optimum taxation depends on the tradeoff between the social costs of taxation and the benefit of public spending, such as providing public goods and income redistribution. The social cost of taxation not only includes the direct cost, but also the resulting deadweight loss or marginal excess burden (MEB) from distortionary taxes (Pigou, 1947; Harberger, 1964; Browning, 1976; Mirrlees, 1971). Smaller MEB means a more efficient taxation system. Reducing the efficiency loss from the distortionary taxes can point to the direction of taxation reform (Piketty *et al.*, 2014). Thus, a lot of studies focus on estimating the marginal excess burden of taxation or the marginal cost of public funds (Snow and Warren, 1996; Fullerton, 1991; Fullerton and Henderson, 1989; Parry and Bento, 1999). Most of these estimates show that the MEB of capital tax is higher than those of labor tax. Recently, some studies have attempted to estimate the tax income elasticity (TIE) to infer MEB (Feldstein, 1999; Saez and Giertz, 2012). Higher TIE usually means higher MEB. The estimates for the TIE using 1980s data are quite high-typically greater than

one (Feldstein, 1995; Lindsey, 1987). More recent estimates using 1990s data have smaller values (Carroll, 1998a,b), which implies smaller MEB that might be closer to 0.5. If we have the information of MEB for an economy, the optimum of recycling of carbon revenue should be directed to reduce the tax associated with highest MEB. On the other hand, after evaluating the different manner of recycling carbon revenue, we may be able to deduce the ranking of MEB of different taxes in the economy.

In this paper, we try to broaden the revenue recycling options by considering a variety of options, and discern the optimum recycling schemes in terms of reducing abatement costs through the comparison of scenarios. Our simulation results suggest that recycling carbon revenue in order to reducing labor or capital income tax or subsidizing investment fares better than simple lump-sum transfer to the consumers or subsidizing the renewable energy supply sector. In the short-term reducing labor income tax, while in the long-term reducing capital income tax or subsidizing investment, have the lowest abatement cost in terms of household welfare.

The rest of paper is arranged as follows. Section 2 briefly introduces the version of model used. Section 3 discusses the scenario and simulation results. Section 4 provides a summary of findings and concludes.

2. The EC-MSMR Model

Computable General Equilibrium (CGE) models are the workhorse for environment, trade and tax policy-related economic analysis. This type of models take into account not only direct effects but also indirect and feedback effects of a policy intervention in a simultaneous multi-market equilibrium. ECCC's multi-sector multi-regional model (EC-MSMR) is an open-economy recursive-dynamic CGE model of the global economy, formulated in MPSGE (mathematical programming system for general equilibrium) (Rutherford, 1999).

In the MPSGE formulation, an Arrow-Debreu general economic equilibrium model is implemented and efficiently solved as a complementarity problem (Mathiesen, 1985). There are "three central variables" and the corresponding complementary equations in the MPSGE formulation, (1) P: commodity prices, including all final goods, intermediate goods and primary factors, emissions permit or quota price or emission tax, and regulatory performance standard shadow price; (2) Y: various activity levels of nested constant returns to scale including production activities, final spending activities, and Armington goods activities; and (3) RA: Rationing agents are the representative agent or "household" in each region of the model; their total income includes the income from endowments such as labor and capital services, and transfers such as taxes received by government entities.

Complementary to those three central variables, there are corresponding fundamental equations, (1) commodity market balance, there is no excess demand for any commodity; (2) zero profit, there is no positive profit for any activity; and (3) income balance, income equals expenditure for any rational agent. These central variables

combined with fundamental equations augmented by auxiliary variables and corresponding complementary constraints that represent endogenous tax or rationing allocation conditions, plus exogenous variables or parameters, form the general equilibrium model system. In the following sections, a non-technical description of the model used is provided. For an algebraic documentation of a previous version of the model see [Ghosh *et al.* \(2012\)](#).

2.1. Regions and sectors of the model

There are 16 regions, 20 basic commodity-producing sectors and three final demand sectors (consumption, governmental spending and investment) in the model aggregated from Global Trade Analysis Project Database version 9 (GTAP 9, see Region Map and Sector Map in Appendices [A.1](#) and [A.2](#)). Of the 20 commodity-producing sectors, electricity sector is split into power generation, transmission and distribution. Power supply sector is disaggregated into various technology of generation: (1) fossil fueled, (2) nuclear, (3) hydro (4) wind, (5) solar, (6) geothermal, (7) biomass, (8) coal integrated gasification with carbon capture, (9) natural gas power generation with carbon capture, (10) biomass power generation with carbon capture, (11) solar power generating with storage. The last four electricity generation technologies are backstop electricity generation technologies that may be activated in the presence of climate policy. There are also two non-electric Backstop Technologies implemented in the model: (1) biomass to liquid, and (2) H₂ supply, which can be substituted for fossil energy use. The crude oil sector in Canada features 7 crude oil supply technologies (conventional and bitumen) and bitumen upgrading/refining: (1) Light Oil Mining, (2) Heavy Oil Mining, (3) Frontier Oil Mining (light oil), (4) Oil Sands Mining (surface), (5) Primary Oil Sands (cold in situ extraction), (6) Cyclic Steam Stimulation Oil Sands, (7) Steam Assisted Gravity Drainage and finally (8) Oil Sands Upgrading (synthetic crude light oil). For the U.S., there is a bitumen refinery sector that is split from refined oil sector and mainly upgrades Canadian bitumen and heavy crude oil into refined oil¹. There is no separation of conventional and unconventional crude oil for U.S. and other regions. In the model, bitumen is only traded between the U.S. and Canada.

2.2. Output activities

Production activities in each region at the sector level are represented by multi-level nested constant elasticity of substitution (CES) cost functions. These cost functions describe the price-dependent use of resources such as capital, labor, energy and material. At the top nesting level in a productive sector, where applicable, a resource input associated with the activities is combined with a CES non-resource composite

¹Given the importance of Canadian bitumen exports to the U.S., the EC-MSMR model explicitly models a bitumen refinery sector.

Figure 1. Output activities.

(KLEM) (Fig. 1). At the second level nesting a CES non-energy material composite (M) is combined with a CES aggregate consisting of energy, capital and labor (KL-E) to produce KLEM composite or final output if there is no resource input.² At the third nesting level, a CES function describes the trade-offs between composites of value added (KL) and energy aggregate (E). At the fourth level the substitution possibilities within value added (K-L) is implemented as a CES function of labor (L) and capital (K). Similarly, within the composite energy nesting level, substitution possibilities are captured by a CES function of electricity and non-electricity energy composite (CGO). At the non-electricity energy nesting level the composite (CGO) is in turn defined as a CES aggregate of coal, oil and gas.

2.3. Goods supply from domestic sources and imports

Regions are linked through international trade. Goods supplies in a region originate from domestic and imports. Following the [Armington \(1969\)](#) approach, supply from domestically produced goods is differentiated from imported goods; and imports from different regions are also differentiated. This treatment helps to accommodate the

²In MPSGE coding, if there is no resource rent, that is, resource rent input equals zero, MPSGE system would ignore this level of nesting automatically and enter into next level nesting CES structure.

cross-hauling observed in trade data. Total supply of a commodity to an economy is formed by a CES aggregator of the domestically produced commodity and the composite imported good of the same kind. The composite imported good in turn is a CES aggregate of the goods imported from a different origin (Fig. 2).

2.4. Welfare

The representative household in each region owns all primary factors (resource, capital, labor and the endowment of time which can be allocated between labor services and leisure), receives factor incomes, rents, transfers and taxes on goods and services. The representative households make tradeoffs between leisure and supply of labor and choose the optimal bundles of consumption and leisure to maximize their welfares subject to a budget constraint; there is no involuntary unemployment. As is shown in Fig. 3, the representative household's welfare is a CES function of composite consumption and leisure. The composite consumption is the consumption of goods and services and represented as a multi-level nested CES function similar to Fig. 1. The parameter of elasticity of substitution between leisure and consumption depends on the elasticity of labor supply and benchmark leisure and labor endowment (Ballard, 1999). In our simulation exercise, the parameter of elasticity of substitution is assumed to be

Figure 2. Armington goods supply of an open economy.

Figure 3. Household welfare.

equal to 0.3, and the amount of leisure is assumed to be equal to 20% of labor supply. Of course different parameter number may produce different results.

2.5. The Recursive-Dynamic formulation of the Model

The model distinguishes between extant capital and new capital. Extant capital is defined as the remaining capital after depreciation and is sector-specific; new capital is formatted exclusively through new investment. Expectation is myopic, that is, investment, consumption, and production decisions are determined only by the economic situation in the current period. New capital and labor services are mobile across sectors but immobile across regions. The saving-investment is modeled through Tobin Q's response to the ratio of capital's return to the cost of investment. In our exercise, the elasticity of investment to this ratio is assumed to be 0.3, which means, when the capital service price relative to the investment cost double, the investment would increase by 30% relative to benchmark. It is also assumed that government spending and the current account balance are fixed for policy comparison purpose.

2.6. Treatment of CO₂ and non-CO₂ emissions

All GHG emissions including CO₂ and non-CO₂ emissions (e.g., CH₄, N₂O, HFCs, PFCs and SF₆) except those from land use, land-use change and forestry (LULUCF) are accounted for in the model. All emissions are converted into CO₂-equivalent using the most recent estimates of respective global warming potential over a 100 year time horizon. The treatment of fossil fuel (coal, oil, and gas) combustion-related emissions is simple and straightforward. That is, CO₂ and non-CO₂ emissions from fossil fuel combustion are linked directly in fixed proportions of its use by respective CO₂ and non-CO₂ emission coefficients. This implies that fossil fuel combustion-related CO₂ and non-CO₂ abatement can occur via inter-fuel substitution or energy savings (by substituting energy inputs for non-energy inputs and/or by a scale reduction of production). Similarly emissions can be reduced by substituting emissions-intensive commodities for less emission intensive ones in final consumption. Process-related emissions are related to the production process but not to fossil fuel combustion and are treated as related to sectoral outputs and top-nesting inputs to production as discussed below.

Modeling process related non-CO₂ emissions and abatement is complicated as a simple relation between inputs used/output produced and emissions cannot be established. For example, no clear relation exists between agricultural crops produced in an acre of land and the amount of methane (CH₄) emitted. However, there are various abatement options available for non-CO₂ emissions. Studies have found that non-CO₂ GHGs have relatively lower abatement costs (Hayhoe et al., 1999; Manne and Richels, 2001; Reilly et al., 1999, 2000). The US Environmental Protection Agency (EPA, 2010) provides country-specific non-CO₂ emission estimates and bottom up estimates of marginal abatement cost curves (MACs) of various non-CO₂ GHG gasses across

different activities. The model incorporates the abatement functions for each non-CO₂ emissions following the approach in Hyman *et al.* (2003).

Non-CO₂ emissions by type of gases are treated as inputs to a multi-level CES production function. In the no-policy baselines, non-CO₂ emissions have fixed proportional linkage with sectoral output, and non-CO₂ emission coefficients are determined based on the EPA estimates of non-CO₂ emissions. In the policy scenario, the substitutions between non-CO₂ emission inputs and other inputs are activated by a parameter of the elasticity of substitution between non-CO₂ emission input and other inputs; thus process-related emissions can substitute for other inputs associated with the output. Figure 4 describes that the modeling approach of the process-related non-CO₂ emissions is an add-on to the production technology structure which is described in Fig. 1. The top nest of Fig. 1 connects to the bottom level of Fig. 4 as composite input. Values of elasticity in these nests are taken from EPPA, which are estimated based on EPA's bottom-up estimates of source/sector/region-specific MACs and Hyman *et al.* (2003) approach.

2.7. Equilibrium conditions

Equilibrium in the model is characterized by market clearing in goods, factors of production, and all other markets in all regions of the model. Prices of goods and factors of production are determined endogenously, which ensures that all primary factors are fully employed and all markets are clear.

Restrictions to the use of GHG emissions in production and consumption are typically implemented through exogenous emission constraints to keep emissions to a specified limit that determine the emission taxes required endogenously or through

Figure 4. Processed related non-CO₂ emissions and abatement.

exogenous GHG taxes that determine the reductions achieved endogenously. Revenues from emission regulation accrue from CO₂ taxes (or, equivalently, from the auctioning of emission allowances) and are recycled back to the economy in a revenue-neutral way in the respective region; the revenue recycling can be in lump-sum transfer to consumers or in other ways which will be explored in this paper.

2.8. Data sources and parametrization of the model

The basic dataset is Global Trade Analysis Project (GTAP) data with the latest version of GTAP 9 (Aguiar et al., 2016). GTAP 9 has the following key features: (1) base year of 2011; (2) global multi-regional input–output tables providing key values economic transactions including production, consumption and bilateral trade for 57 sectors and 140 regions; (3) initial tax margins for inputs, output and trade; (4) fossil fuel related CO₂ emissions by sector by fuel; (5) values of parameters, such as elasticity of substitution in value-added and trade. In a satellite table GTAP also provides detailed data for emissions of non-CO₂ GHGs such as CH₄, N₂O and F-gas for the base year. GTAP's country and sector profile are aggregated to the model's region and sector profile through region and sector mapping as are shown in Appendices A.1 and A.2. For Canada, the base year's economic accounts from Statistics Canada's 2011 L-level National Input-output tables aggregated to model's sector profile. Canada's energy and emissions including CO₂ and non-CO₂ emissions data come from Environment and Climate Change Canada's E3MC model results (Environment Canada, 2014).

The EC-MSMR model's forward calibration is carried on recursively and based on the assumptions about economic growth and technological changes of productions (automatic energy efficiency improvements (AEEI)). For Canada, the assumptions used are implied in the projections of economic output, energy use and emissions from ECCC's E3MC model; for other Annex 1 regions, the technology and economic growth assumptions come from UNFCCC's submitted Second Biennial Reports (BR2) (UNFCCC, 2016); for all other regions, the calibration assumptions come from USA Energy Information Agency (EIA)'s 2016 International Energy Outlook (EIA-IEO, 2016) on economy, energy and CO₂ emissions. For non-co2 the emissions projection and bottom-up estimates of country-specific MACs across different activities came from the US Environmental Protection Agency (EPA, 2010).

The value of elasticity parameters related to capital, labor, energy and material substitutions come from the empirical estimates of Okagawa and Ban (2008). The Armington trade elasticity parameter values are taken from GTAP data, and values of elasticity parameters in Non-CO₂ nesting are taken from EPPA, which are estimated based on Hyman et al. (2003) approach.

3. Simulation Scenarios and Results

In this section, we will first discuss the scenario setup and then analyze the simulations results.

3.1. Scenarios setup

The scenario setup involves the carbon price, coverage, and carbon revenue recycling method.

To understand the role of alternative revenue recycling schemes, as an illustration, we adopt estimates of the social cost of CO₂ by the US EPA (2016) at a 3% discount rate as the carbon pricing schedule used in the simulation, as is shown in Table 1.³

For GHG coverage, we focus on the fossil fuel combustion related CO₂ emissions in the U.S. Although it would be ideal to include all GHG emissions from all sources in the U.S., from the point of view of practical policy, some processes related to non-CO₂ GHG emissions such as from industrial, waste and agricultural are difficult to monitor, and there are other regulatory policies in place, for example, methane regulation for the oil and gas sectors. So in the exercise, we just include the fossil fuel combustion-related CO₂ emissions in carbon pricing simulations, because of the ease of collection and do not significantly increase administrative costs. Moreover, they are the major component of GHG emissions; in 2015, around 80% of GHG emissions in 2015 in the U.S. are from fossil fuel combustion.

As described before for keeping carbon tax revenue-neutral, we consider different ways of carbon revenue recycling. Of the six scenarios analyzed here the first three are derived from the EMF32 Inter-model Comparison of US Greenhouse Gas Reduction Policy Options group (Table 2). The other three are designed to broaden the recycling options. These scenarios involve choosing between a combination of carbon price, coverage, and carbon revenue recycling options.

Table 1. Social cost of carbon (SCC) by year (2010\$/tCO₂).*

Year	SCC at 3% discount rate
2020	44
2025	48
2030	52
2035	57
2040	62
2045	67
2050	72

*Note: except for the scenario REW_a, in which a cap of CO₂ emission as the same as in LUM is set.

³In the modeling exercises, we also tried other schedule of carbon taxes; the simulations results are by and large similar. We simply use these prices as carbon price schedule, which does not mean we endorse them as social cost of carbon as per se.

Table 2. Simulation scenarios.

Scenario name	Scenario description (carbon revenue recycling mechanism)
LUM	Lump-sum transfer to consumers
CAP	Reduction of capital income tax rate
LAB	Reduction of Labor income tax rate
INV	Subsidy to investment
REW	Subsidy to renewable electricity production
REW_a	Subsidy to renewable electricity production, but with the same CO2 emission as in LUM

In the first scenario (LUM) all carbon revenues collected from the price schedule in Table 1 are transferred to representative households in a lump-sum manner. In the second (CAP), the carbon revenue is used to reduce capital income taxes while the third (LAB), the revenues are used to reduce the existing labor income tax rates. In the fourth scenario (INV) carbon revenues are used as subsidies to investment. The idea here is that promoting investment leading to building up of capital stock will effectively reduce energy use and emissions; however, in EC-MSMR model, an aggregate production or activity function is used, so new vintage effect on emissions of new investment may not be well reflected. In the fifth (REW) scenario carbon revenues are used as subsidies but only to renewable electricity production. Lastly, in scenario six (REW_a) for the sake of comparison on the equal footing of carbon emissions, instead of carbon tax, a cap on CO₂ emissions (at the same level as that which resulted from the carbon tax in the first four scenarios) is imposed.

The Renewable energy technologies, such as solar and wind, are evolving fast but still immature and in the rapidly declining part of the learning curve. Research and development in the area and removal of barriers such as infrastructural constraints (e.g., investment in smart grid) can bring large spillover effect and network benefits. Thus, subsidizing renewable energy is justified from the point of view of not only emissions reduction and climate change, but also economic growth and technological change. However, in our model, the CES representation of activity or technology may not be able to fully reflect those perspectives of renewable energy technologies.

Before going over the simulation results, we should keep these caveats in mind. Incidentally, we see that the reductions in emissions are more or less the same in the first four scenarios.

3.2. Scenarios results

We will use the carbon revenue, the tax or subsidy rate, welfare and GDP change relative to business as usual (BAU), to evaluate the scenarios.

Before assessing the policy scenario, we discuss briefly the baseline or BAU economic growth and emissions, which provide the reference points for comparing

Figure 5. Baseline real GDP for U.S. (unit: 2010 billion US\$).

policy scenarios. Figure 5 shows the baseline GDP for the U.S., suggesting that the U.S. GDP will more than double from 2015 to 2050, though the annual growth rates will be trending down a little bit in the future. Figure 6 shows the calibrated baseline CO₂ and GHG emissions, indicating the downward trend for both CO₂ and GHG emissions in the future for the U.S. The downward trending of both CO₂ and GHG emissions comes from the continuous energy efficiency improvements and shift to renewable energy use.

Since carbon pricing in our exercises only covers CO₂ emissions, we only discuss the covered CO₂ emission abatement in policy scenarios. As is shown in Fig. 7, CO₂ emissions abatements are by and large similar across all scenarios except in

Figure 6. Baseline CO₂ and GHG emissions for U.S. (unit: MMT CO₂e).

Figure 7. U.S. CO₂ emissions in under various scenarios (unit: MMT CO₂e).

renewables subsidy scenario, abatement is little bit higher than other scenarios because the subsidy to renewables would make renewable energy use more competitive, leading to a little bit more abatement. By and large, CO₂ emission abatement is determined by the carbon price schedule; sectoral variation may only have secondary effects. With CO₂ emission abatement being on the similar stand, we can evaluate any differences through the comparison of the impact on welfare or GDP.

3.2.1. Baselines of economy and emissions

In this paper the scenario results are described as percentage of BaU level of various indicators such as welfare, consumption and GDP. It is therefore, useful to first describe the underlying BaU projections of key economic indicators used for policy analysis. The U.S.'s GDP is forecast to grow moderately in the future as is shown in Fig. 5; however, the CO₂ and GHGs emissions are trending down because of energy efficiency improvements and expanded deployment of renewable energies, as shown in Fig. 6

3.2.2. Carbon revenue and policy instrument indicators

As is shown in Table 3, the generated carbon revenues are almost the same under different revenue recycling regimes and under a given carbon pricing, except for the scenario of subsidy to renewable energy or alternative scenario of subsidy to renewable energy. The outcome is plausible because all the revenue recycling options investigated other than the last two scenarios are geared toward all economic activities and as such they are not specific to any particular sector and therefore it makes relatively very little in terms emissions reduction across scenarios. Under fixed carbon taxes, the carbon

Table 3. Carbon revenue (2010 US Billion \$).

Scenario	2020	2025	2030	2035	2040	2045	2050
LUM	187	194	179	170	160	152	151
CAP	187	194	179	170	161	152	151
LAB	187	194	179	170	161	152	151
INV	187	194	179	171	161	152	151
REW	135	130	121	121	124	126	126
REW_a	61	60	58	67	69	74	71

revenue is directly related to covered CO₂ emissions, so the different revenue recycling would result to the almost the same covered CO₂ abatement. The results also indicate that in real terms, the carbon revenue may increase from 2020 to 2025, and decline afterwards, because the increasing carbon price may lead to more decreasing emissions and also partly because even in BAU, the CO₂ emissions are also projected to decline in the future.

However, relative to GDP, as is shown in Table 4, the ratio of carbon revenue to GDP continuously declines from around 1% in 2020 to 0.4% in 2050.

Under revenue-neutral carbon tax, the revenue recycling will lead to increase in consumption in case of lump-sum transfer to consumers as additional money becomes available to households. In case of recycling toward capital and labor tax the effective tax rates will fall. The rate of subsidy increases if the revenue is used for promoting investment of renewable energy production. The relative magnitude of various rates would decrease as the generated carbon revenue decreases from the second round effect on output or renewable energy production shown in Table 5.

Figure 7 shows the CO₂ emissions under different scenarios. To understand the abatement associated under the scenarios these should be compared with those in Fig. 6 under the BaU. Except the scenario REW, all other scenarios have by and large similar level of CO₂ emissions. For the scenarios REW, because subsidy to renewable energy is also a supplementary climate policy; thus under the same carbon price, it can achieve more CO₂ emissions reduction.

Table 4. Ratio of carbon revenue to GDP.

Scenario	2020	2025	2030	2035	2040	2045	2050
LUM	0.97%	0.89%	0.73%	0.63%	0.53%	0.44%	0.39%
CAP	0.97%	0.89%	0.73%	0.63%	0.53%	0.44%	0.39%
LAB	0.97%	0.89%	0.73%	0.63%	0.53%	0.45%	0.39%
INV	0.97%	0.89%	0.73%	0.63%	0.53%	0.44%	0.39%
REW	0.71%	0.60%	0.50%	0.45%	0.41%	0.37%	0.33%
REW_a	0.31%	0.28%	0.24%	0.25%	0.23%	0.22%	0.19%

Table 5. Recycling instrument indicators.

Scenario	2020	2025	2030	2035	2040	2045	2050
LUM	1.43%	1.33%	1.11%	0.95%	0.80%	0.68%	0.61%
CAP	−3.95%	−3.61%	−2.97%	−2.53%	−2.13%	−1.80%	−1.60%
LAB	−1.67%	−1.53%	−1.25%	−1.07%	−0.89%	−0.75%	−0.66%
INV	−5.47%	−4.98%	−4.06%	−3.44%	−2.87%	−2.41%	−2.13%
REW	−83.59%	−68.76%	−57.10%	−57.12%	−60.28%	−60.39%	−60.02%
REW_a	−80.26%	−48.47%	−45.25%	−41.98%	−37.35%	−36.48%	−33.06%

Note: The numbers represent implied consumption increase (LUM), capital income tax rate change (CAP), labor income tax rate change (LAB), investment tax rate change (INV), and renewable electricity output tax rate change (NEW and NEW_a).

3.2.3. Welfare impact

Welfare is a key measure to make judgement between alternatives policy options. In the model, as stated above, the welfare is a measure of combined consumption of goods and services and leisure. In our model, a representative consumer/household will make tradeoff between consumption and leisure subject to budget constraint. In the case of recycling through labor tax reduction, the consumer will have more choice space compared with the case of lump-up transfer, because marginally, the consumer can increase labor supply to increase the welfare when facing less tax on labor income. In the case of capital tax reduction or investment subsidy, the cost of invest would decrease, and investment demand would increase following Tobin’s Q response. As a result, consumption may decrease more compared the case of lump-sum transfer in the short period. However, in later on periods, the cumulated capital through previous invest can boost the choice space for consumer, and would have a better welfare outcome compared with other scenarios. It should be noted that full effect of revenue recycling in this model may be somewhat muted due to recursive-dynamic nature of the model. That is to say if firms are allowed to look forward and anticipate future changes in subsidy, it is expected that firms would smooth out investment and impacts could be higher but directionally same. In the case of subsidy to renewable energy, the renewable energy production may be boosted and replace fossil combustion to some extent; therefore, it can achieve more emission abatement but consumer will face less favorable constraint compared with other scenarios.

Table 6 shows the welfare change relative to baseline or Business as Usual (BAU). A few observations can be made from the table:

- (1) As the carbon price increases in later periods, the welfare loss in every scenario tends to increase compared with respective BAU levels.
- (2) The scenario of reducing labor income tax would bring less welfare loss relative to BAU than the scenario of lump-sum transfer to consumers. This is because the labor income tax reduction not only gives income back to consumers but also

Table 6. Welfare change relative to baseline (%).

Scenario	2020	2025	2030	2035	2040	2045	2050
LUM	-0.09	-0.14	-0.27	-0.41	-0.49	-0.54	-0.57
CAP	-0.19	-0.16	-0.23	-0.35	-0.43	-0.47	-0.51
LAB	-0.07	-0.12	-0.24	-0.38	-0.47	-0.52	-0.55
INV	-0.22	-0.16	-0.22	-0.34	-0.41	-0.46	-0.49
REW	-1.28	-1.88	-2.13	-2.18	-2.05	-1.92	-1.78
REW_a	-0.45	-0.63	-0.85	-1.08	-1.20	-1.29	-1.30

change the trade-off between leisure and working, which would improve consumers' welfare because the better options are available to choose.

- (3) Compared with the scenarios of labor income tax reduction, a capital tax reduction or investment subsidy scenario show more welfare loss in earlier periods such as 2020 and 2025 (as consumer reduce current consumption), but less welfare loss in later on periods such as from 2030 onwards because capital tax reduction or investment subsidy would boost earnings from capital investment.
- (4) Comparing between the capital income tax reduction and increased investment subsidy scenarios, it appears that the later has higher impacts on investment as the subsidy it targeted toward new investments not on all capital. As a result the welfare loss under investment subsidy is a little larger in the earlier periods but less in the later on periods compared with the scenario of capital income tax reduction.
- (5) The two scenarios of sector-based support such as subsidy on renewable electricity generation either under same carbon price or CO₂ cap would fare worse compared with other scenarios mostly because they are not as productive as other options would generate given the cost considerations.

3.2.4. Impact on US GDP and its components

As is shown in Table 7, from the point of view of real U.S. GDP, the consistently best scenario that brings the least abatement cost is that of invest subsidy, followed consecutively by capital income tax reductions, labor income tax reduction, lump-sum

Table 7. GDP change relative to baseline (%).

Scenario	2020	2025	2030	2035	2040	2045	2050
LUM	-0.17	-0.18	-0.24	-0.30	-0.34	-0.36	-0.38
CAP	-0.05	-0.03	-0.08	-0.15	-0.19	-0.23	-0.26
LAB	-0.09	-0.11	-0.18	-0.25	-0.30	-0.33	-0.35
INV	-0.02	0.01	-0.04	-0.11	-0.16	-0.20	-0.23
REW	-0.53	-0.88	-1.07	-1.13	-1.08	-1.04	-0.98
REW_a	-0.17	-0.31	-0.42	-0.55	-0.63	-0.70	-0.72

Table 8. Investment change relative to baseline (%).

Scenario	2020	2025	2030	2035	2040	2045	2050
LUM	−0.42	−0.30	−0.16	−0.01	0.07	0.08	0.10
CAP	0.54	0.54	0.53	0.59	0.59	0.53	0.51
LAB	−0.36	−0.26	−0.14	0.00	0.08	0.09	0.10
INV	0.78	0.74	0.69	0.72	0.70	0.62	0.59
REW	2.28	2.51	2.33	2.05	1.71	1.42	1.18
REW_a	0.93	0.79	0.96	1.06	1.03	0.97	0.86

transfer; and still the worst scenarios are those of subsidy to renewable energy either under same carbon price or same CO2 emissions cap. Investment subsidy or capital income tax reduction would encourage broad level investment and capital formation and thus have better performance in terms of impact on GDP measurement.

Investment and consumption are the major two components of GDP. The options of recycling carbon revenue may have different impacts on the two components. Table 8 shows the impact on the investment. It indicates the following observations: (i) the scenarios of subsidy to renewable energy would bring relatively larger investment compared with BAU because deployment of renewable energy demands more new investment; (ii) the next are the scenarios of investment subsidy and capital income tax reduction that would also increase investment compared with baseline in every period; and (iii) in later-on periods, in all the chosen policy scenarios, the investment would increase relative to BAU, because renewable and clean technologies are more capital intensive and with the increasing carbon price, the investment demand for the renewable and clean technologies would increase and thus increase the total investment.

Table 9 shows the impact on consumption, a result that is consistent with the welfare change shown in Table 6, with a little bit larger magnitude, suggesting also that the scenario of labor income tax fares best in earlier periods, the scenario of investment subsidy fares best in later-on periods, and the scenarios of subsidy to renewable energy fares worst in every periods. That is because the investment subsidy

Table 9. Consumption change relative to baseline (%).

Scenario	2020	2025	2030	2035	2040	2045	2050
LUM	−0.13	−0.19	−0.32	−0.45	−0.54	−0.58	−0.61
CAP	−0.22	−0.19	−0.27	−0.39	−0.46	−0.51	−0.54
LAB	−0.04	−0.10	−0.24	−0.38	−0.48	−0.53	−0.56
INV	−0.24	−0.19	−0.26	−0.37	−0.45	−0.49	−0.53
REW	−1.41	−2.02	−2.26	−2.29	−2.14	−2.00	−1.84
REW_a	−0.50	−0.68	−0.91	−1.14	−1.26	−1.34	−1.35

would boost investment and next period's capital factor and capital income. On the other hand, subsidy to the renewable energy may boost renewable energy development but forgo the revenue for the consumers.

3.2.5. Cumulative total welfare change⁴

Economists tend to use welfare as a criterion to help make choices among policy options because welfare maximization is the key objective of the households in the model. However, as observed above, the welfare criteria may lead to different conclusions in different periods. Thus, we need to integrated the measures in various periods and calculate cumulative welfare change for the scenarios concerned. One issue with calculating cumulative welfare effect is that of what discount rate should be used (for a detailed discussion, see, [Goulder and Williams \(2012\)](#), [Arrow et al. \(1995\)](#), [Stern \(2007\)](#)). In this paper, we use a discount rate of 3%, to calculate the cumulated welfare change up to 2050, the end period of our model simulation since that discount rate is used by EPA to calculate the SSC in Table 1. The cumulated welfare change is calculated as the sum of discounted welfare change of every period. Table 10 shows the cumulative welfare impacts in different scenarios. It indicates that the optimum choice of scenario would depend on which ending horizons are used to calculate the cumulated effects.⁵ Shorter time horizon may favor the choice of labor tax reduction while longer horizon may favor the choice of investment subsidy. The reason lies in that the scenario of labor income tax reduction tends to lead to least welfare loss in earlier periods whereas the scenario of investment subsidy tends to lead to least welfare loss in later periods. Examination of Table 10 also suggests that:

- (1) The scenarios of recycling carbon revenue to sector-specific support such as renewable energy subsidy may fair worse than the scenarios of general-purpose or

Table 10. Cumulative welfare effect (2011 billion US\$).

Scenario	2020	2025	2030	2035	2040	2045	2050
LUM	-10	-26	-54	-94	-141	-190	-240
CAP	-21	-39	-63	-98	-139	-182	-226
LAB	-8	-20	-46	-84	-129	-176	-225
INV	-24	-42	-65	-99	-138	-180	-223
REW	-145	-350	-572	-788	-983	-1158	-1314
REW_a	-51	-120	-208	-315	-429	-547	-660

⁴General welfare in climate change policy context should include avoided damage. Since damage is not modeled in our model, here we measure the welfare change in terms of effectiveness, that is, the least abatement cost.

⁵Discount rate may also matter.

across-the-board tax reduction or subsidy such as labor income tax reduction, capital income tax reduction or investment subsidy or even simply lump-sum transfer to the consumer.⁶

- (2) The scenarios of recycling revenue to reduce labor income tax, capital income tax or subsidy investment fare better than the scenario of simple lump-sum transfer in longer horizon.

3.3. Caveats

Distributional effects are not considered in our analysis, but in climate policy consideration, income inequality may be an important issue when revenue recycling regimes are designed.

The learning curve, spillover, network effect of renewable energy technologies are not represented in the model, so the results may bias against the subsidy to the renewable energy policy. The complex tax structure may not be represented in the model. Recursive dynamic feature may not be realistic, because when consumers and firms may smooth their consumption and investment when anticipating the carbon pricing and taxation change. More sensitivity study may be needed in terms of choice of parameter values.

4. Conclusion

Carbon pricing may generate substantial revenue which may be recycled to economy to reduce the economic cost of GHG abatement. There are various revenue recycling options available to governments. These includes using the revenue to reduce existing distortionary taxes or other market imperfection in the economy. The benefits from these recycling options will vary depending upon the nature and magnitude of distortions or market imperfections. In this paper, six revenue recycling options for a specified schedule of carbon tax scenario for the U.S. over the period 2020–2050 are analyzed using a version of Environment and Climate Change Canada's multi-sector and multi-region CGE model (EC-MSMR). These includes: (i) lump-sum transfer to consumers, (ii) labor income tax reduction, (iii) capital income tax reduction, (iv) subsidy to investment; and (v) subsidy to renewable wind and solar energy and (vi) an alternative to scenario (v). Simulation results from these scenarios are compared in terms of economic impacts as welfare and GDP. A number of conclusions follow from the analysis of the simulation results:

- (1) Overall recycling the carbon revenues toward across the board reduction of distortionary taxes such as capital or labor tax seems to work better compared to sector-specific support such as renewable energy subsidy in the U.S. context.

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⁶Intuitively, a general subsidy or tax reduction works better compared to a specific one unless there are market failures or market imperfections in the specific sector. In this model, we abstract from any market imperfections. Renewable subsidies are expected to induce the production of renewable energy which is carbon neutral or less carbon intensive compared to conventional energy. It appears that given the current cost structure and our assumption of no market imperfection renewable subsidy is not expected to yield better outcome compared to other general scenarios such as the lump-sum transfer to household.

- (2) Recycle the carbon revenue toward labor income tax reduction, capital income tax reduction or investment subsidy seems to yield better efficiency outcome than simple lump-sum transfer of revenue to the households.
- (3) Under the carbon tax recycling revenue to labor income tax reduction appears to bring least welfare loss in earlier periods, while recycling it toward capital tax reduction or increased investment subsidy would bring least welfare loss in later periods. The relative desirability between labor income tax reduction on the one hand, and capital income tax reduction or increased investment subsidy on the other hand would depend on the rate of discounting and horizon.
- (4) In terms of impacts on GDP, the best choice seems to be recycling carbon revenues toward subsidy to investment, followed by capital tax reduction both of which is expected to boost investment and capital formation and reduce the negative impact on GDP in every period and on consumption in later periods.
- (5) Finally, results presented in this paper are based on underlying modeling assumptions, the data and the values of parameters used in the model calibration. The results in this paper should therefore be viewed as directional only.

Acknowledgments

We would like to thank the editor and three anonymous referees for their constructive comments and feedbacks on the previous version of the paper. We also thank Derek Hermanutz, Monique Brugger and participants at the EMF 32 and the meetings of the Canadian Economics Association for useful discussions and comments on the earlier versions of the paper. We are grateful to Christoph Bohringer and Thomas Rutherford for helping us with several aspects of basic model development used in this paper. Views expressed in this paper are those of the authors and do not reflect those of Environment and Climate Canada or the Government of Canada.

Appendix A

Table A.1. Region map.

Model region code	Constituents
CAN	Canada
JPN	Japan
RUS	Russian Federation
USA	United States of America
BRA	Brazil
IND	India
MEX	Mexico
KOR	South Korea
ZAF	South Africa
AUS	Australia
NZL	New Zealand
OPEC	14 countries comprising OPEC
EUR	28 European Union members
CHN	China and Hong Kong
SAM	South American Countries except Brazil, Ecuador and Venezuela
ROW	Res of the World

Table A.2. Sector map.

Model code	Constituents
OIL	Refined oil products
GAS	Natural gas works
OMN	Mining (MINING)
LUM	Wood and wood-products (WOODPRO)
PPP	Paper-pulp-print (PAPERPRO)
CRP	Chemical industry (CHEMICAL)
NMM	Non-metallic minerals (NONMET)
ELE	Electricity and heat
OMF	Other manufacturing (INONSPEC)
CNC	Construction (CONSTRUC)
ATP	Air transport
COL	Coal transformation
CRU	Crude oil
AGR	Agricultural products
PRM	Primary metal manufacturing
TEQ	Transport equipment (TRANSEQ)
FPR	Food products (FOODPRO)
TWL	Textiles-wearing apparel-leather (TEXTILES)
TRN	Transport
SER	Commercial and public services

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