Regional Burden Sharing of GHG Mitigation Policies
A Canadian perspective

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Preliminary – Comments are welcome

Abstract

The distribution of the burden of cost arising from the reduction of greenhouse gas (GHG) emissions is a contentious issue in policy discussions; more so among regional jurisdictions in the federalist countries with decentralized authorities over environmental regulations. In this paper, we develop a multi-region computable general equilibrium (CGE) model of the Canadian economy to assess the implications of different burden sharing rules governing the national GHG abatement policy with a cap-and-trade system of emission permits. In addition to assessing the impacts of traditional regional emissions allocation rules that involve intra-regional transfers of wealth, we consider a particular emission allocation that avoids such transfers, which may be a more palatable option given the context of likely fierce negotiations over the issue. Our results provide differing outcomes depending on the allocation policy in use. The CGE framework is also able to shed light on the transmission mechanisms that drive the results underlying the policy options.

Key Words: Emissions entitlements, regional allocation, burden sharing rules, no prior entitlement, EBA, EPC, CCI, EI, MI, GFA

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1. Introduction

The threat of global warming has induced the international community to setup a goal towards reducing atmospheric accumulation of greenhouse gases (GHG) caused by anthropogenic reasons. International negotiations such as those held in the United Nations led Conference of the Parties (COP) provide a forum for international community to negotiate a deal aimed at achieving that goal. The hope is that the negotiations will lead the way for countries to arrive at legally binding commitment levels in order to reduce global emissions. What generates heated discussions in these negotiations is the issue of burden sharing that ultimately stems from the issue of distribution of welfare costs among the participating countries. Not surprisingly, the issue of 'fair' burden sharing has continued to recur as a key theme in the climate protocol negotiations since the Kyoto round (Ringius et. al, 1998).

The topic remains as contentious, and has the potential to generate as heated a debate, even within the national boundaries; more so, where the specific country under scrutiny has a non-unitary system of government (i.e. a decentralized federalist structure) like Canada, the U.S. and Belgium (Boucekkine and Germain, 2009; Boucekkine et. al, 2010). The scope of this arises since, in some of these countries, while the federal government has the authority to sign international agreements relating to environmental issues, regional jurisdictions have to decide on their implementation plans.

While debates may exist on the specifics of an approach for implementing a plan, a perception that is equally shared by the federal and regional governments is that the reduction of GHG emissions is costly. Implementation of any plan for curbing emissions, thus, requires some form of consensus on burden sharing among the regional governments. In a decentralized system of governance, however, negotiations towards an agreement are generally marked by each region willing to bear the minimum cost while letting the others shoulder the brunt of the national mitigation target (i.e. the free-riding effect).

Moreover, the costs arising from this equity-efficiency trade-off also tend to differ not only over available policy options, but also from one region to another. In other words, heterogeneity in the composition of regional economies plays a critical role in the debates over cost sharing. Thus, for successful adoption of a binding accord and its subsequent implementation, the regional incidences of GHG burden costs must be carefully investigated. Such an investigation not only ought to identify the optimal policy from the set of feasible policy options, but also needs to ground it on equity principles with firm ethical standing[1]. This is the primary focus of this study. In particular, based on recent equity-efficiency debate in the literature concerning GHG mitigation efforts and its impacts on different industrial sectors, we present an assessment of six policy scenarios, where we explicitly consider the heterogeneity in energy outlook and the associated burden sharing consequences for the regional economies. We use Canada as the country of investigation for this purpose.

In the context of international climate policy negotiations, existing literature offers a wide range of criteria for evaluation of the burden-sharing rules involving efficiency and equity considerations (Torvanger and Ringius, 2002). These rules may generally also be applicable in the regional context. Within the cap-and-trade (CAT) framework, equity in these negotiations typically implies assigning implicit (and often *a priori*) emission

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[1] For an excellent discussion on equity principles considered in international negotiations, see Rose (1992 and 1998). Barrett (1992) also provides some valuable discussions on the moral and ethical aspects of some widely recognized equity principles.

entitlements (i.e. assigning emission rights). Except for the unlikely structure of regionally segregated emission permit markets that might exist within the same national boundary[2], such entitlement schemes also entail the contentious issue of inter-regional transfer of scarcity rents that occurs through trading of rights in a common (single) national emission permit market. In fact, this issue has long been a feature of the international negotiations on climate change, and was a major factor in the U.S. withdrawal from the Kyoto Protocol (Jacoby and Reiner, 2001; Sue Wing, 2007).

Given that emission intensity as well as the extent of access to emission-benign technology varies across regions, from a rent-seeking perspective, regional authorities have incentive to lobby for specific permit allocation policies that favor them over the others. Such lobbying efforts will try to keep costs as low as possible or even gain additional rents at the expense of others. This generally characterizes the existing emission allocation policies (e.g. emission-based allocation of permits or permit allocation based on emissions per capita) that are often highlighted in the literature. The race to rent-seeking, however, not only makes negotiations highly contentious but also largely diminishes political palatability of available emission allocation policy options.

The challenge is then to devise a mechanism that can avoid this contentious issue of inter-regional transfer of emission rents. In addition, the mechanism should be also capable of achieving the national objective while rendering equitable distribution of burden costs across the regional jurisdictions. In this paper, we attempt to devise such a scheme. We call this the *no prior entitlement* (NPE) scenario in which, as the name suggests, no *ex-ante* emission entitlements are assigned to the regions[3]. Regions, in turn, receive, in a lump-sum fashion, their share of scarcity rents *ex-post* based on residual (i.e. equilibrium) levels of regional emissions. We also provide a comparative analysis on the performance of NPE scheme relative to the existing schemes in the literature. In particular, using a static computable general equilibrium model of Canada, we assess welfare costs of five other permit allocation schemes. These are – emission based allocation (EBA or the proportional allocation of rights based on the past levels of emissions); allocation based on: emissions per capita (EPC); converging carbon intensity (CCI); efficiency index (EI); and the multi-criteria index (MI)[4]. A detailed discussion on each of these allocation schemes and the underlying equity rationale is provided in section 3.

While existing literature presents several policy instruments that are capable of achieving the targeted reduction in emission levels, market-based instruments (MBI) are usually the most preferred ones (Goulder et al. 1999; Fullerton and Metcalf, 2001). This is because MBI can achieve the specified objective at the least cost. Furthermore, MBI also possess the dual benefit of being an efficient instrument (since they function via market mechanisms) in addition to being less burdensome due to their ability to incorporate equity considerations. The current policy schemes considered for the proposed scenarios also fall within this category.

A salient feature of the MBI is that, depending on the emission rights allocation policy, it may generate scarcity rents for the recipients of emission permits that can be used to mitigate the negative costs of abatement. These revenues come from unabated emissions, i.e., the targeted level of emissions assigned to the country. Thus, in the form of permits, the

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[2] We rule out this possibility in this paper.

[3] NPE scheme can be thought of as a fictitious auctioning of emission permits where, given demand and supply of permits, the auction determines the equilibrium price of the permit. The federal government then uses the equilibrium price to allocate emission proceeds to individual regions according to their residual level of emissions.

[4] Note that each of these schemes renders a specific value judgment on equity and caters to a specific set of considerations.

distribution of the unabated emissions among the regional jurisdictions will have some implications on the regional costs and welfare impacts of GHG mitigation. This is the framework employed in this paper. In particular, within the CAT structure with a single national emission permit market where regions can trade permits freely, we explore policy options/scenarios that consider equity issues in the form of allocation of emission permits to the regions. Emission allowances thus primarily take two forms under these scenarios – entitlement versus no prior entitlement (NPE).

While under the entitlement-based scenarios emission rights are allocated to the regions *ex-ante*, under the NPE scenario emissions allowances are allocated based on each regions' residual (i.e. *ex-post*) level of emissions. For both of these broad allocation schemes, however, a regional government distributes its lump-sum share of scarcity rent *ex-post* among its economic actors (more specifically, to the representative household of each region).

For the current purpose, we divide Canada into six regions – Alberta, Atlantic Provinces, Ontario, Other Prairie Provinces, Québec, and British Columbia and the Territories[5]. Once regional emissions allowances are identified under the six schemes considered in the paper, regions are free to trade permits in the single national emission permit market[6]. The scarcity rents, thus generated through trading, is then recycled to the representative households[7] using the lump-sum recycling method. Hence, within the model framework, while the allocation principle essentially tackles the equity concerns of the competing regions, permit trading (and the recycling method of scarcity rents) addresses the efficiency aspect of the equation.

The remainder of the paper is organized as follows. In the next section, we provide a review of recent relevant literature. A thumbnail sketch of the model proceeds after that. In particular, this section includes description of various sectors – i.e. households, firms, and the governments, as well as the equilibrium conditions of the model, and the closure rules. A detailed discussion on the six policy schemes examined in the current paper and their equity implications follows the next. The salient features from the model-runs are presented in the ensuing results section. Finally, the paper wraps-up with some concluding remarks.

2. Review of the Relevant Literature

In recent times, several studies have attempted to probe into the regional incidences of GHG mitigation costs. In the Canadian context, most of these papers, however, focus primarily on various federal proposals (Snoddon and Wigle 2007 and 2008, and MKJA Associates 2009). In the U.S. context, on the other hand, papers focus on both federal and state level policy options (Sue Wing, 2007 and Sue Wing and Kolodziej, 2008). In almost all of these papers, the general emphasis centers around implementing alternative policy packages that aim to ameliorate the uneven burden costs arising from the national carbon emissions control target.

Using a regional static CGE model of the Canadian economy, Snoddon and Wigle (2007) provide estimates of the aggregate and regional costs, measured in terms of the loss in regional GDP, that are associated with different climate change policy packages. They assume that the federal government uses a proportionality rule (i.e. EBA) for allocating Canada's total international endowment of emission permits to their provincial counterparts, who in turn, also use an EBA scheme to distribute their share of permits. The authors also

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[5] The choice of regional segregation, in effect, corresponds to the available set of data.
[6] In other words, this ensures efficiency through the functioning of the emission permit market.
[7] Each region is assumed to have one representative household.

compare this scheme to Jaccard, Rivers and Horne (2004) plan. The EBA scheme is based on charging all emitters a price equal to the world price of carbon permits. This constitutes the key feature of the model – namely, that all emitters face the same incentive to abate at the margin. While the authors identify that equal incentive serves to achieve cost-effectiveness condition for the prescribed policy packages, they neither consider pre-existing distortions in the economy, nor do they account for uneven burden costs on various industries within the regional economy. We take up these issues in this paper.

Using a static CGE model of U.S., on the other hand, Sue Wing (2007) emphasizes two issues – the effects of declining factor remuneration on welfare, and the welfare impacts of using different revenue-recycling schemes (i.e. recycling at the federal or state level). Sue Wing shows that diminishing returns to factor arises from the scale and homogeneity of interstate commodity markets. The imperfect factor mobility, captured in the modeling structure, reinforces this process through curtailment of the expansion of import-competing industries in States, which import large quantities of domestically-produced energy. Together, these raise the burden costs and make it uneven for some States at the expense of the others. Sue Wing, however, further demonstrates that the effects of uneven burden costs can be mitigated through appropriate method of revenue recycling when an auction permits scheme is used. He demonstrates that when revenue is recycled at the State level, it generally distributes the burden cost over all the States (especially the large States) via terms-of-trade effects. If, on the other hand, revenue is recycled at the federal level, the burden cost seems to intensify for the carbon based energy-intensive States at the benefit of the large States. Results derived from our model somewhat correspond to this qualitative finding. However, the recycling method and the policy schemes considered in our paper are different from the ones implemented by Sue Wing (2007).

While these papers consider various within-country issues, they ignore one specific issue – namely, the overall impact on welfare and the burden cost when regional governments are accorded no prior emission entitlements versus the case when they are assigned such entitlements *ex-ante*. We consider this issue in this paper. Using the lump-sum method of revenue recycling to the representative households, we investigate how welfare changes when different Canadian regions use the entitlement approach for allocating emission permits (EBA, EPC, CCI, EI and MI) versus the case when emission permits are allocated based on no prior entitlement (NPE) principle. We use a static CGE model of Canada's regional economies to address this question in this paper. In-so-doing, we particularly pay heed to the heterogeneous economic structures of the provincial economies and identify its effects on the overall regional welfare.

3. The Model

In this section, we describe the model developed for the analyses presented in this paper. Current model belongs to the family of static CGE models where Canada is considered a small open economy vis-à-vis the rest of the world. Within the national boundary, the country is divided into six regions where regional economies are characterized by the free flow of goods and services.

The model presented in this paper entails multi-sector, multi-region structure that entails the characteristics of the individual regional economies. Thus, heterogeneity among regional economies is captured into the model framework. Nesting of production structure used in the model is somewhat akin to that of Dissou (2006) with modifications being carried out especially in the markets for primary factors of production. Overall, the model generally features a disaggregation of the production and consumption sectors in each region. A peculiar feature of the model is that it captures not only the trade flows of each region with the rest of the world but also the flows between and among these regions.

3.1 Households

We assume a single representative household in each region. These representative households maximize their utility by choosing the optimal level of aggregate consumption and leisure. As in the standard economic theory, households are the owners of primary inputs (i.e., labour and capital). They derive their income from payments to primary factors. Further, their income is augmented by exogenous transfers from the government and from the rest of the world (ROW). A fixed portion of household's income is used to pay income taxes to the government, while its savings are a linear function of its disposable income.

The aggregate consumption of the representative household, in turn, is allocated over different consumption goods using an expenditure minimization principle. A system of three nodes represents various composition of commodity usage through a CES aggregator function. These aggregator functions allow us to mimic the real life substitution behaviour exhibited by the households of the modeled regions. Furthermore, the nested structure of the model allows for substitution, on one hand, between energy and non-energy products and, on the other hand, among various energy goods. Utility maximization subject to budget constraint makes it possible to derive household demand for each commodity in each region.

3.2 Firms

In each of the six regions of Canada considered in this study, the production sector is disaggregated into 19 industries producing 26 commodities. Each industry has a representative firm that has access to a constant-returns-to-scale (CRS) technology. Similar to other general equilibrium models, the production structure is broken down into a sequential decision process that offers some interesting substitution possibilities among inputs.

Foremost is the composite output, which is a constant elasticity of substitution (CES) function of the composite input of capital-labour-energy and the aggregate input of material-mobile factors. The former is obtained by combining labour input with the aggregate of capital-energy input using a CES production process. In turn, the aggregate input of capital-energy is obtained by combining physical capital and the composite input of energy the latter of which is a Cobb-Douglas (CD) aggregate of electricity and the non-mobile fossil fuels. Refined petroleum products, natural gas, and coal are combined using a CES function to produce the non-mobile fossil fuel energy input. The aggregate intermediate input, on the other hand, is a CES aggregator of material inputs and mobile energy inputs. While a Leontief aggregation is used to produce the former, a CES function of Gasoline and Diesel is used to combine the latter. All firms operate in a competitive environment and maximize profits to determine output supply and their respective factor demands.

3.3 Governments

Government sector is kept simple in the model. We consider in each region only one consolidated level of government. Government expenditure on goods and services is held fixed in real terms. Its other outlays consist of transfers to the households.

Revenues for government are raised from indirect taxes on regional transactions and from direct taxes on payments to primary factors. In addition, government also raises revenue from indirect taxes on international transactions. These taxes introduce pre-existing distortions in the regional economies and thus set the stage for interesting debate in terms of the rationale for a given region's predilection towards specific emissions control policy from the set of available choices.

3.4 Trade: Regional and International

Trade is modeled in multi-stages. Referring to Armington (1969), regional and foreign goods are distinguished by their origins. This specification has the advantage of accommodating the incidence of cross-hauling both regionally and internationally. On the demand side, regional imports from rest of the regions (ROR) are distinguished from imports from the rest of the world (ROW). We consider, imports from ROR as imperfect substitutes.

A three-level nested CES function allows us to distinguish between international and regional imports. At the first level, regional absorption (i.e., the sum of the demands for final and intermediate use of goods and services) is a CES function of regionally produced goods and the aggregate of imports. At the second tier, imports are a CES composite of regional imports and imports from ROW. Finally, the aggregate of regional imports is modeled as another CES function of imports from all of the regions that make-up the ROR. This nested structure allows the representative agent's decision to take place through a multi-step budgeting process. A cost minimization principle allows the determination of the optimal level of each component of the final demand.

Akin to imports, exports are also differentiated according to their destinations. A revenue maximization rule is used in this context. For each region, we use a three-tier nested constant elasticity of transformation (CET) function to capture the imperfect substitution between different components of the representative firm's supply of total output. At the initial node, a firm's total output is a CET composite of regional supply and aggregate exports. Again, a CET function is used at the second tier to allocate total exports between ROR and ROW. Finally, a third CET aggregator function allows firms to re-allocate regional exports among the remaining regions.

While a small country assumption is used to characterize Canada's relationship with the ROW essentially signifying that the world price of imports and exports are held fixed, the prices of the bilaterally traded goods among the regions are fully endogenous. These prices are determined by the market clearing conditions for inter-regional trades between any two regions. Finally, given the national structure, the model does not require current account balance to hold for each region individually; rather, it demands that the sum of the current accounts of all the regions be balanced for Canada as a whole with the ROW.

3.5 Equilibrium Conditions and Closure Rules

The general equilibrium of this model is represented by a static allocation of goods and factors supported by a vector of prices such that the following conditions are met:

i) equilibrium in regional goods markets for all regions;

ii) equilibrium in regional factor markets for all regions; and

iii) the balance of payment equilibrium for Canada as a whole.

The models *numéraire* is the nominal exchange rate with the ROW. We consider three closure rules in the model. The first rule applies to the regional government accounts. We keep government savings in each region constant to its benchmark value. Government transfer to households is the equilibrating variable that adjusts to respect the constraint on government savings.

The second closure rule pertains to the equilibrium condition between expenditures on investment goods and savings, which is achieved at the national level, thanks to the regional nature of the model.[8] The model is saving-driven in the sense that investment expenditures are endogenous and are determined by the amount of total available savings. The latter is equal to the sum of the savings of regional households, firms, and the governments. Note that total Canadian foreign savings is the sum of the foreign savings of all regions. The sum of intra-regional savings (trade balances), on the other hand, is equal to zero.

The final closure rule deals with Canada's external account. We assume that Canada's total current account is equal to its foreign savings, which we maintain fixed. Note that this does not preclude external account of each region to vary but only requires the aggregate to be constant. This equilibrium condition is achieved by an adjustment of the real exchange rate, which is defined by the relative prices of traded and non-traded goods.

4. Emissions Permit Allocation Schemes – Description of the Simulations

Policy experiments within two broad scenarios – *entitlement* versus *no prior entitlement* (NPE) to emission rights – are considered, which constitute the focus of the paper. Table 1 provides a snapshot of the counterfactual simulations performed in this paper. The impacts of the NPE principle in allocating emission permits are compared with those of five other entitlement based allocation system, namely – (i) emission based allocation (EBA); allocation based on: (ii) emissions per capita (EPC); (iii) converging carbon intensity (CCI); (iv) efficiency index (EI); and (v) multi-criteria index (MI). Once an allocation scheme is chosen, based on which the regions trade amongst themselves, the resulting scarcity rents generated through emissions trading are then distributed by the regional governments within their own jurisdiction in a lump-sum fashion.

Table 1: Simulation schemes

Scenarios	Entitlement	No Prior Entitlement
Allocation schemes	EBA, EPC, CCI, EI, MI (Once entitlements and regional emission permit needs are known, regions trade residual permits among themselves in the national emission permit market).	NPE (No trade occurs since regions get emission rights based on residual (i.e. equilibrium) level of emissions).

We, hence, present a total of six allocation schemes each representing a specific policy option for allocating Canada's carbon emission rights. The equilibrium condition on emissions, as identified in equation [1] below, confirms that Canada's total level of carbon emissions, which is the sum of regional emissions over all regions ($E = \sum_R E_R$), does not exceed its national target ($\overline{E}$).

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[8] In contrast, in a multi-country model, equilibrium between saving and investment expenditures will be achieved in each country.

$$E = \overline{E} \qquad [1]$$

where $E_R = E_{H,R} + \sum_j E_{Q,j,R}$ [2]

and, $R_R = \Phi_{*,R}\overline{E}$ [3]

here, $E_{H,R}$ = household emissions in region R; $E_{Q,j,R}$ = industrial (combustible) emissions (i.e. emissions related to the use of inputs) produced from good j in region R; R_R = total emission rights received by region R; and $\Phi_{*,R}$ = exogenous parameter that reflects the allocation principle used for initial distribution of emission permits to a region.

Since regional level of emissions are endogenously linked to the level of economic activity in each region, endogenously determined scale-back factor is used to ensure that all region collectively do not exceed exogenously allocated level of emission rights that correspond to the national emissions target[9].

Note that while five of these schemes are based on a prior distribution of permits each reflecting a specific equity criterion, one scheme – NPE – does not entail any prior distribution of emission permits. Notwithstanding the differences, NPE reflects it own equity principle that is akin to the outcome-based allocation of emission permits. This is since, under this scheme, emission rights are distributed among the regions based on their residual (or equilibrium), as opposed to anticipated, level of emissions. The model is, therefore, designed to answer a specific, yet crucial, question that has not been explored in the literature: whether prior allocation of emission permits serves the equity consideration relatively better than a scheme where no such prior allocation is allowed? In order to contextualize this question within the policy schemes studied in this paper, we now provide some discussions on the simulation scenarios performed in this paper.

4.1 Emissions Based Allocation

Allocation of emission rights based on proportional level of historic emissions is the most commonplace principle cited in the literature. In essence, this relates to the sovereignty principle, which implies that each individual, or an economic entity, is guaranteed some rights and resources. The principle of sovereignty is commonly observed in international environmental treaty-making and institution-building, and is adopted in the United Nations Framework Convention on Climate Change (UNFCCC)[10].

$$\Phi_{EBA,R} = \frac{E_{R,Base}}{\sum_R E_{R,Base}} \qquad [4]$$

here, $E_{R,Base}$ = regional emissions at the base period

One way to interpret the principle is to reduce GHG emissions in proportion to existing levels of emissions (Ringius et. al, 1998). The EBA policy in the context of the current paper reflects regional entitlement of emission permits in proportion to each regions historic level of emissions, where aggregate (i.e. national) reduction target of GHG emissions

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[9] See the list of equations provided in the Appendix A for further details.

[10] According to one of the UNFCCC's preambles: "States have, in accordance with the Charter of the United Nations and the principles of international law, the sovereign right to exploit their own resources pursuant to their own environmental and developmental policies, and the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction."

is distributed following the proportionality rule (equation [4]). In terms of the equity and fairness, this implies that all regions are essentially left at their status-quo state.

4.2 Allocation Based on Emissions Per Capita

The EPC criterion is another frequently cited allocation principle in the literature. This rule reflects the egalitarian approach – the principle of equal rights for all persons – and is mostly concerned with the concept of equality. In the context of climate change, the principle implies that every individual has the same right to use the atmosphere and is allowed the same right to emit GHG irrespective of their geographic location.

$$\Phi_{Pop,R} = \frac{Pop_{R,Base}}{\sum_R Pop_{R,Base}} \qquad [5]$$

here, $Pop_{R,Base}$ = regional population at the base period

The concept essentially entails the underlying notion that emission permits belong to the individuals, not to the governments, where each individual is entitled to the same amount of permits. In terms of operationalization (equation [5]), this means that regional emissions targets are distributed in proportion to population, where the aggregate reduction target of GHG emissions is respected as the binding constraint.

4.3 Allocation Based on Converging Carbon Intensity

While neither EBA nor EPC reflects a region's carbon consumption behavior, the CCI, proposed by Rowlands (1997), presents an allocation scheme that recognizes this phenomenon. The underlying principle for this allocation scheme is related to the concept of horizontal equity, which calls for all persons in the same group to be treated equally (resembling, to some degree, the principle of sovereignty). The principle of horizontal equity implies equal treatment being accorded to all members that belong to a group. This principle is motivated by the requirement to equalize the burden of abatement costs across all regions.

The allocation scheme corresponding to the CCI is operationalized based on converging carbon intensity of GDP (i.e. carbon emissions per unit of regional GDP), which is used as an indicator of efficiency (i.e. the lower the carbon intensity of an economy, the higher its efficiency). The underlying idea essentially implies that more stringent emission reductions should be prescribed for economies where actual efficiency is low. Emission entitlements under this scheme, therefore, mandate high initial reductions for economies with the high carbon emissions levels. Emission reductions are mandated until the region's carbon intensity of GDP equals that of the region with the next lowest score. This is reflected in equation [6] - [8] below.

$$R_R = \upsilon\, \Phi_{CCI}\; GDP_R \qquad [6]$$

$$\sum_R R_R = \overline{E} \qquad [7]$$

$$\Phi_{CCI} = \frac{E_{R,Base}}{GDP_{R,Base}} = \min\left\{ \frac{E_{R,Base}}{GDP_{R,Base}} \right\} \text{ for } R = 1, 2, 3, \ldots \qquad [8]$$

here, υ = endogenously determined scale-back factor that ensures the attainment of the national emissions mitigation target; $E_{R,Base}$ = regional level of emissions at the base period;

$\underline{E}_{R,Base}$ = lowest regional level of emissions at the base period; $GDP_{R,Base}$ = regional GDP at the base period; and Φ_{CCI} = lowest regional carbon intensity of GDP at the base period.

Whereas this allocation policy recognizes efficiency aspect in regional level of carbon emissions, it does so relative to the national rather than the regional backdrop. In a decentralized federalist economic union like Canada, this remains at odds since regional economies enjoy rather a larger degree of autonomy in the union. In addition, while this allocation policy reflects principles of horizontal equity, it does not provide sufficient incentives for already efficient regions (i.e. regions with low *regional* carbon intensity) for achieving the efficiency in the past. An equitable distribution of emission rights would require recognition of past efficiency in terms of special allowances be allotted to such regions, which can also be expected to have lower marginal abatement costs.

4.4 Allocation Based on Efficiency Index

Proposed by Gupta and Bhandari (1999), allocation scheme based on the EI approach addresses the issue identified above. Their approach, in a way, is a hybrid of the EBA (that includes proportional percentage reduction of emissions) and the CCI approach (which incorporates the efficiency cost criterion). Under this policy scheme, regions that have achieved high efficiency (reflected in terms of the low *regional* carbon intensity of GDP relative to the *national* carbon intensity of GDP) in the past are accorded more emission permits. Therefore, the following adjustment is suggested:

$$R_R = \upsilon\, E_{R,Base}\ \left(1 - \mathrm{GAP} * \Phi_{EI,R}\right) \qquad [9]$$

$$\sum_R R_R = \overline{E} \qquad \text{[same as 7]}$$

$$\Phi_{EI,R} = \frac{E_{R,Base} \big/ GDP_{R,Base}}{\sum_R E_{R,Base} \Big/ \sum_R GDP_{R,Base}} \qquad [10]$$

where $\Phi_{EI,R}$ represents the regional efficiency index that is applied to the percentage reduction in emissions rather than the level of emissions.

The efficiency index is thus defined as the carbon intensity of a region, divided by the carbon intensity of the country. Unlike CCI approach, the EI approach hence measures regional carbon intensity (i.e. relative to its own economy) vis-à-vis the national carbon intensity. It, therefore, addresses both horizontal and vertical equity.

Although EI based allocation performs better in addressing equity concerns, it still suffers from one specific criticism – this criterion entails rather a narrow economic base in that it only considers regional carbon intensity and ignores any other criteria that capture the characteristics of region-specific economic composition. This criticism is more relevant in the context of Canadian economic union since different regions in the union seem to entail different economic structures (i.e. manifested through its industrial composition) that differ significantly from one another.

4.5 Allocation Based on Multi-Criteria Index

The above criticism is addressed in the permit allocation scheme that is based on the MI approach. Proposed by Ringius et al. (1998), the approach combines a set of six indicators (population, CO_2 emissions, CO_2 emissions per GDP, CO_2 emission per capita, regional GDP, and regional GDP per capita) to calculate emission reduction target for each region.

As indicated in equation [12] below, the index defines emission reduction for each region as a percentage of emissions in the reference year. The formula includes the following indicators: CO_2 emission per capita (A), GDP (B), emissions per unit of GDP (C), and GDP per capita (D):

$$R_R = \upsilon\, E_{R,Base}\ \left(1 - \text{GAP} * \Phi_{MI,R}\right) \qquad [11]$$

$$\sum_R R_R = \overline{E} \qquad [\text{same as } 7]$$

$$\Phi_{MI,R} = \left[\omega_A \left(A_R \Big/ \sum_R A_R \right) + \omega_B \left(B_R \Big/ \sum_R B_R \right) + \omega_C \left(C_R \Big/ \sum_R C_R \right) + \omega_D \left(D_R \Big/ \sum_R D_R \right) \right] \qquad [12]$$

These are understood as indicators for emission entitlement, size of a region, regional energy efficiency, and a region's ability to pay, respectively. The resulting $\Phi_{MI,R}$ is the index for region R and ω_A to ω_D are the weights that add up to 1[11]. The parameter υ is a scaling factor, determined endogenously such that the emission reductions by all regions become equal to the national target in the aggregate.

The MI approach addresses several equity principles at the same time by combining a subset of four indicators in the formula. CO_2 emissions per capita can be considered to represent the egalitarian equity; GDP per capita addresses the vertical equity; emissions per GDP reflects the horizontal equity; and the GDP represents the size of economy while the overall level of CO_2 emissions in a base year reflect the proportional equality. The MI approach, thus, characterizes a high degree of flexibility and is able to incorporate characteristics of the regional economic composition.

4.6 Allocation Based on No Prior Entitlement of Emission Rights

Depending on their implications on a region's own economy, while all five entitlement-based schemes identified above address various equity concerns with some degree of satisfaction, they all involve inter-regional transfer of scarcity rents generated through trading of emission rights in the national emission permit market. Thus, they have the potential to engender fierce political debates depending on the outcome of any specific permit allocation policy.

In light of the importance of political appeal for likely implementation of any allocation policy vis-à-vis the contentious issue of inter-regional transfer of scarcity rents, we propose the sixth allocation scheme – NPE – and evaluate its performance relative to the others.

$$R_R = E_{R,Residual} \qquad [13]$$

As evident in equation [13], unlike the other five schemes, this scheme does not involve prior allocation of emission rights and hence avoids any transfer of emission rents across regions. Under this policy scheme, emission rights are distributed based on residual level of emissions ($E_{R,Residual}$). The scheme, hence, reflects outcome-based allocation

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[11] No objective numerical values are proposed for the weight of each indicator, therefore leaving the scope of possible negotiations among the regions. For the current purpose, we chose $\omega_i = 0.25$ for $i = A, B, C, D$.

principle and entails welfare implications that yield results that are different than that of the ones from other five entitlement-based allocation schemes.

In all the six simulations, however, we consider a cap-and-trade emissions trading framework where permits are traded in a single domestic market across the regions[12]. For an illustrative purpose, we consider a 25% reduction of total emissions in Canada in comparison to the benchmark[13]. For a good understanding of the differences among the simulations, the ensuing discussions on results are focused on the basic mechanisms at play for the NPE simulation, and on how results change for the other five policy simulations relative to the base period.

5. Description of the Baseline Data

The model is calibrated to a customized dataset that is sourced from Statistics Canada for the year 2005. The business-as-usual (BAU) dataset entails detailed disaggregation both at the regional and sectoral levels such that the confidentiality provisions are respected. Emissions data by fuel type are built using information supplied by Statistics Canada and conform to the emissions forecasts contained in the Analysis and Modeling Branch report (1999).

Using these data we calculate emission factors for different fossil fuels and emission intensities by region and by industry. Values used for various behavioral parameters, on the other hand, are borrowed from previous studies on Canada, such as Ab Iorwerth et al. (2000) and Wigle (2001) and are not very different from the values used in many other general equilibrium models of Canada or the United States. The calibration of the model involves using the SAM, exogenous parameters, first-order conditions, and steady state conditions to recover other parameters in the behavioral functions and the values of the non-observed variables to reproduce the reference situation. To this end, we use the calibration procedures frequently employed in static and dynamic general equilibrium models as explained in Dissou (2002), Keuschnigg and Kohler (1994), and Mansur and Whalley (1984).

Table 2a and 2b above provide a general snapshot of the share of emissions and GDP levels of six Canadian regions in 2005, while Table 2c provides the values used for the elasticity of substitution parameters. Data indicate that while Alberta's share of national CO_2 emissions equals that of Ontario's (both roughly at 30%), Ontario (at 38.4%) contributes more than twice as much to national GDP as Alberta (at 17%). This implies that Alberta has an emission intensity level that is more than twice the emission intensity level of Ontario. The BAU data also indicate that Québec is the third most polluting region of Canada, although it contributes less than half of the pollution level as compared to Alberta or Ontario (at 12%). Québec also contributes roughly 20% to Canada's national GDP, which signifies an emission intensity level that is smaller than that of Ontario's. The BAU data thus reveal contrasting positions of these regions in terms of the level of emissions vis-à-vis their level of economic activity.

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[12] It is important to understand that, under NPE, no actual trading of emission rights occurs. The structure of the model, however, endogenously determines the equilibrium price of emission rights that is identical to the price that would have resulted had the permits been physically traded in the national emission trading market. To ensure the successful attainment of reduced national target of emissions level, we use an endogenously determined scale-back factor that guarantees a fixed aggregate supply of emission permits. Coupled with the aggregate regional demands for emission permits, the capped aggregate supply, thus, determines the equilibrium price of emission rights.

[13] 2005 is the benchmark year.

The data reveal that the political response to any uniform permit allocation policy that can achieve the national emission mitigation target would vary from one region to another. This fact serves as the primary motivation for this paper. As indicated above, in this paper we perform an independent evaluation of six such allocation policies that corresponds to different equity criteria. We now turn to the next section that provides the results of this evaluation.

6. Results

Unless otherwise mentioned, all the results presented in this paper are expressed as a percentage deviation from the reference situation (i.e. the BAU scenario). The results from different simulation are contained in Tables 3-16. The permit price affects the prices of polluting goods and thus all relative prices in the economy. It has both direct and indirect effects, characterized by the changes in regional production costs, composition of aggregate demand, and household welfare.

6.1 National Impacts

Table 3 presents some aggregate results for Canada. We observe that all indicators register a percentage decline under all policies except for household disposable income and aggregate consumption. Given the revenue recycling (i.e. lump-sum[14]) system used by each regional government to redistribute its share of emission rents to households, it is not surprising to see that household disposable income, and consequently the real aggregate consumption, rise. Disposable income increases due to the emission rent transfer that the households receive because of the lump-sum recycling method.

For the remainder of indicators – GDP at market price, exports, imports, investment demands and CO_2 emissions by household and industry sources – at the aggregate level, the differences from one policy scenario to another is somewhat minor. All emission permit distribution policies typically reduce industrial emissions by a large amount (around 28%). Households bear fewer burdens in the overall effort to reduce emissions, thanks primarily to the lump-sum revenue recycling policy. Larger industrial brunt of emissions reduction seems to translate into lower demand for investments (around 4%). National emissions reduction also takes toll on exports and imports (down by 2%) in addition to registering a reduction of 0.6% in the overall GDP of the economy.

These aggregate results, which summarize the impact of the policy change on Canadian economy as a whole, however do not provide information on the variety of regional adjustments. The regional impacts that shed light on the equity aspects are discussed below. We first highlight some salient aggregate results at the regional level followed by results that elucidate adjustments in some of the industry sectors of interest in individual regions. In-so-doing, we offer intuitive explanations and highlight the main transmission mechanisms at work.

6.2 Regional Aggregate Impacts

Table 4 provides results regarding the impact of various policy schemes on regional GDP. Out of the six Canadian regions, results indicate that the economy of the Atlantic region (i.e. Newfoundland and Labrador, Prince Edward Island, Nova Scotia, and New Brunswick) generally contracts the most followed by that of Alberta's under almost all policy schemes. Québec, on the other hand, experiences the least contraction closely followed by Ontario and British Columbia and the Territories (BCT).

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[14] Lump-sum revenue recycling amounts to transferring the value of permits to the households.

When comparing NPE policy with rest of the entitlement-based policy schemes, all regions tend to suffer almost the same amount of GDP losses under the former relative to the latter schemes. Québec, however, seems to do slightly better under NPE relative to the EPC and the CCI schemes (-0.4% as oppose to -0.5%) while Alberta experiences the opposite (-1.1% versus -0.9%).

Interestingly the story reverses when we consider percentage change in welfare[15]. While, due to the lump-sum revenue recycling method, all regions generally experience improvements in (household) welfare, Alberta does so relatively more under the NPE scheme compared to the remaining regions. Québec, on the other hand, gains the least (0.1%) followed by the Atlantic provinces and the BCT (0.2%). This is linked to both the policy schemes (which render varying amounts of emission rent transfers to each region) and the recycling mechanism (i.e. lump-sum) that typically benefit Alberta and Other Prairie Provinces (OPP comprises of Manitoba and Saskatchewan) relative to rest of the Canadian regions.

In terms of the entitlement-based schemes, with EPC and CCI, while Alberta heavily suffers from welfare losses (-2.5% and -1.2% respectively), Québec gains the most under those policies (1.4% and 1.0%). This is not surprising since with relatively large population base, Québec receives larger share of emission rights under the EPC scheme. With the CCI policy, on the other hand, while other regions receive less number of rights due to their high emission intensity relative to their respective regional GDP level, because of Québec's improved performance in historical level of emissions, it again receives more permits and consequently scores high in the welfare ranking.

This somewhat consolidates with EI and MI policies that not only look into the efficiency aspect, but also take into account the economic burden (under the EI) and the regional characteristics (under the MI). With both of these policies, welfare performance of the oil-rich Prairie Provinces improves while Ontario's welfare levels deteriorate only marginally relative to the EPC and CCI policies. Québec, on the other hand, suffers from substantial welfare losses under EI and MI schemes compared to the EPC and CCI policies. However, this does not imply that absolute welfare metrics fall in these regions. In fact, under MI policy, our model calculations reveal that even for Québec the absolute welfare level increases by 0.2%, while it increases by 0.3% and 1.1% for Ontario and Alberta respectively. To put these measures into the context, calculation shows that the corresponding increase in weighted welfare[16] level in Canada is 0.5%.

With the EBA policy that distributes emission rights based on past levels of emissions, however, Prairie Provinces (i.e. OPP plus Alberta) benefit the most at the expense of Québec and Ontario since they receive a high share of permits relative to the others, which they are able to trade as a net seller in the national emission trading market. This brings in net transfer of scarcity rents into Alberta and OPP from rest of the regions.

Table 6 provides a snapshot of the value of permit revenues received by various Canadian regions. Table 7, on the other hand, provides the unit price of emission permits under various policy schemes. Evidently, Alberta and Ontario receive the largest share of permit revenues under different allocation schemes while Atlantic and Other Prairie Provinces receive the least. Two factors influence the size of a region's share of emission

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[15] Note that the index of welfare change does not take into account the environmental improvement due to the reduction in GHG emissions. The measure is an indication of the percentage change in the household consumption in the BAU situation that would yield the same utility level as the one with the policy change.

[16] Regional share of aggregate consumption is used as the weight for calculating change in the overall Canadian welfare level.

revenues – allocation scheme in use (i.e. entitlement-based versus no entitlement-based schemes) and the scale of the economy. While Alberta's share is due largely to the allocation scheme itself, Ontario's share is influence by both of these factors. Price of emission permits, on the other hand, seems not to vary considerably from one policy to another. It hovers around approx. \$49 per ton of CO_2.

It is, however, also evident that under the entitlement-based schemes the dollar amount of emission permit purchase varies considerably among the regions depending on the chosen policy option. While attempting to identify the relative position of each region as a net buyer or seller of emission permits when an entitlement based policy is used, as indicated in Table 8, we observe that all Prairie and Atlantic Provinces emerge as the net seller where the remaining regions turn out to be the net buyer of emission permits in the national market under the EBA policy. The scenario drastically reverses under the policy schemes EPC, CCI and EI where Québec and Ontario emerge as the net seller of permits to the remaining regions. Nonetheless, when the MI policy, which takes into account of the regional characteristics, is implemented the intensity of the situation withers away. Interestingly, with the MI policy while Québec continues to be a net seller, Ontario becomes a net buyer of permits like Alberta.

These results are inspired by the emission rent transfer mechanisms that is entailed in each policy option. EBA, being based on the historical emissions level, naturally provides more permits to Prairie and Atlantic Provinces thus making these regions a net seller of permits. EPC scheme, on the other hand, provides more permits to Québec and Ontario as it is based on per-capita emissions level. CCI and EI also render similar outcomes since these policy schemes reward small emitters over the large emitter like Alberta. MI scheme reduces the impact of EI policy since it also takes into account the regional economic structure and the emissions history in addition to rewarding the efficient emitters.

Table 9 provides a snapshot of the compliance burden experienced by the regions that emanates from the rent transfer aspect. In particular, it provides the percentage change in the share of CO_2 permit purchase relative to a region's own permit endowment under each policy scheme. Evidently, Alberta and Atlantic Provinces suffer under the EBA policy (14% and 15% respectively) whereas BCT, Ontario and Québec gain (11%, 11% and 13% respectively). Alberta, however, suffers the most from EPC policy (169%) while Québec is the largest beneficiary under the scheme (-44%). Not surprisingly, with EPC policy Alberta and OPP along with the Atlantic Provinces, benefit the least when Québec and Ontario benefit the most. With CCI, MI and EI policies Alberta's and Atlantic Provinces' burden gradually reduces while that of Québec's and Ontario's increases with mixed results being observed for the OPP.

Results of the policy impacts in terms of percentage change in total emissions are presented in Table 10. For Prairie and Atlantic Provinces being historically the large emitting regions, it is not surprising to observer that, with the implementation of (any) policies, reduction in their emissions levels drift around 26-36% relative to the pre-implementation stage. Emission reduction in Québec, Ontario and BCT, on the other hand, floats around 16-17%.

As explained in the model description section, we treat labour market in the model as geographically segmented. An upshot of this is that the equilibrium wage varies across the regions even though it is identical across the industry sectors of a given region. Table 11 and 12 provide results regarding the impacts on regional wage rates and labour supply, respectively. Overall the results indicate a mirror reflection of the qualitative results subsumed in policy impacts on regional GDP. More than anything, perhaps the information in these tables underscores the importance of incorporating regional economic characteristics into the policy stance.

On the superficial level, we observe that with all policy schemes, regional wage rate and consequently the labour supply fall. When observed more closely, however, results show that the impact of policy implementation is more subdued for large regional economies like Ontario and Québec relative to the smaller ones. This occurs since with the contraction of regional economy stemming from the implementation of (any) CO_2 emission reduction policy, demand for labour falls. Hence the fall in the wage rate. However, that makes labour relatively cheaper. Through feedback loops then the productive sectors of the economy substitutes labour for more expensive inputs into the production process, giving a boost in the wage rate. Consequently, the fall in the wage rate moderates a little. The regional economic characteristics come into play when we, however, concentrate on the relative intensity of these impacts. Irrespective of the chosen policy, regions which have more CO_2 intensive productive sectors (such as those of the Prairie and Atlantic Provinces) suffer from larger fall in wage rate and labour supply since they are unable to make greater substitution in the production process due to the nature of their industry composition relative to the other regions.

6.3 Regional Sectoral Impacts

The multi-region, multi-sector structure of our model yielded large quantity of data for the six policy simulations performed in the paper. In light of the basic focus of this paper and for brevity's sake, however, in this section we present a subset of the results that bring forth the salient features in terms of the impacts of each policy scheme on some regional sectors of interests.

In particular, we concentrate on three big regions – Alberta, Ontario, and Québec – as these regions relatively get more affected by the choice of any particular policy scheme. Our choice of regions is further motivated by regional governments' disparate views on how to mitigate climate change issues in these jurisdictions. We also look into the performance of some of the industry sectors, in particular those of – oil and gas, utilities, basic chemicals, and other manufacturing sector – within these regions in order to bring out further insights at the industry level. Again the choice of these industry sectors is inspired by the high share of emissions of these sectors in the base period. Arguably, implementation of policy schemes studied in this paper can relatively put more burdens on these sectors, thus, creating an uneven distribution of mitigation costs across the industry sectors. Given the focus of the paper, these sectors, therefore, become natural candidates of interest and hence assist in highlighting the impacts of different policy schemes vis-à-vis the brunt of the climate change mitigation costs.

Tables 13a to 13c provide sectoral impacts of change in the total output in the regions of Alberta, Ontario, and Québec. In general, the largest fall in output is experienced in basic chemicals under all policy schemes across all three regions. While the paper industry turns out to be the sector with second largest fall in Alberta, for Ontario and Québec it appears to be the oil and gas and mining industries, respectively. Whereas in the utility producing sector Québec seems to contract the least followed by Ontario and Alberta, in the other manufacturing sector Alberta experiences the largest decline in output followed by Québec and Ontario. Interestingly results indicate that Alberta's output in oil and gas sector, in fact, slightly increases under all policy schemes while for Ontario it decreases substantially. This seemingly surprising outcome signifies, relative to the other regions, Alberta's ability to make greater adjustments (e.g. through value-added substitutions) in this sector[17]. Overall these differences in the impacts underscore varying composition of regional economies and validate the necessity of incorporating regional characteristics in designing the policy schemes.

When we compare these industries over all policy schemes, results indicate that NPE policy performs better relative to the entitlement-based policies across most of the industry sectors. In particular, while the MI policy, (relative to other entitlement-based policies) mostly aligned with the regional economic structure, performs quite the same as the NPE policy, the latter has the added benefit of being able to avoid politically contentious issue of inter-regional transfer of scarcity rents. This makes the NPE policy politically more appealing and, hence, a better candidate among all the policy options.

Tables 14a to 14c present results in emissions reduction across the industry sectors. For Alberta, complying with the national emissions reduction target translates into the largest reduction in emissions in the utility producing sector followed by the basic chemicals and the paper industries. This, however, differs for other two regions. In Ontario while utilities and basic chemicals industries shoulder most of the emissions reduction efforts followed by the oil and gas sector, in Québec basic chemicals contribute almost twice as much in emissions reduction efforts as in the utilities and other manufacturing industries. When we compare the results over the policy schemes, by and larger, similar qualitative inferences emerge as it does for the output indicator. We find that the MI policy scheme generates impacts that are similar to that of the NPE scheme. However, the latter scheme precludes inter-regional transfer of scarcity rents and, hence, appears to be a superior policy candidate.

Tables 15a to 15c provide results for changes in regional demand for value-added for three specific industries – utilities, basic chemicals, and oil and gas. As the results indicate, Alberta experiences the largest fall in value-added demand in basic chemicals and the second largest fall in utilities among all the regions. This explains the corresponding large fall in outputs of these sectors in Alberta. It is interesting to observe that while Ontario also experiences similar decline (though of lesser magnitude), the corresponding reduction in value-added demand in Québec for these industry sectors are very small. This is due largely to the structure of industry composition in Québec. It also signifies Québec's lesser ability to substitute for value-added inputs relative to other regions in order to comply with the national emissions reduction target. The picture reverses for the oil and gas sector, where Alberta seems to demand more of value-added inputs relative to a decline in the same in Ontario. Contrary to Québec's situation, this indicates Alberta's ability to substitute for value-added inputs in oil and gas sector that can help the region to attain its emission reduction goal. When we consider all policy schemes, again the results indicate relatively better performance of the NPE scheme as compared to the other entitlement-based policies.

Finally, Table 16a and 16b presents household consumption of output produced by two industry sectors – utilities and other manufacturing. As revealed in the benchmark data, since the utility producing sector emits large quantities of effluents, implementing any emission reduction policy scheme essentially translates into raising the cost of production for this sector, which in turn causes price of utilities to sore, ultimately leading to a decline in the output demand. The results confirm this and indicate that Albertans shrink their demand

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[17] A significant part of emissions in Oil and Gas sector tend to be process emissions, which are not easily abated. The results obtained for Alberta, therefore, can also be due to the fact that the current model only captures combustible emissions.

the most while residents of BCT show least contraction of utility demands. In terms of consumption of other manufacturing products, results reveal a general rise in the demand across all regions under all policy schemes. This is largely due to the lump-sum method of recycling emission rents as it essentially enhances purchasing power of the households, who are the owner of productive factors in the economy.

Overall a comparison of all six policy schemes generally demonstrates the relative appeal of the NPE policy over the others. Particularly, even though the former scheme performs similar to the MI scheme, it precludes the politically contentious issue of the inter-regional transfer of emission rents.

7. Concluding Remarks

In this paper we examine two broad categories of emission permit allocation policies, namely the entitlement versus no prior entitlement (NPE) based policies. Most commonly cited policies in the literature (e.g. emission based allocation of permits or permit allocation based on emission per capita) generally fall within the former category. An upshot of the entitlement based policies is that they entail the contentious issue of transfer of scarcity rents among economic units that occurs through the permit trading system. Consequently, even though these policies may possess excellent ethical properties, they may not have sufficient political appeal for them to be put to implementation. Non-entitlement based policies, on the other, may not suffer from this lack of political palatability as they preclude such transfers of scarcity rents. The issue is then to devise such a policy and examine its properties vis-à-vis the entitlement based policies. The paper does so by providing detailed comparison of five entitlement based policies with a newly devised non-entitlement based policy that we call the NPE policy.

More specifically, using a static computable general equilibrium model of six Canadian regions (i.e. Alberta, Atlantic Provinces, Ontario, Other Prairie Provinces, Québec and British Columbia and the Territories), in this paper we assess welfare cost of six allocation schemes. While five of these policy schemes (i.e. emission based allocation of permits, EBA; allocation based: on emission per capita, EPC; converging carbon intensity, CCI; efficiency index, EI and multi-criteria index, MI) are based on prior entitlement of emission rights, the NPE scheme does not entail any prior allocation of emission permits.

These results, derived from the six simulations performed in this paper, reflect both equity considerations as well as the extent of emission rent transfers that are entailed in each policy option. The EBA policy, being based on the historical emission levels, provides more permits to the Prairie and Atlantic Provinces, thus, making these regions a net seller of permits. EPC scheme, on the other hand, provides more permits to Québec and Ontario as it is based on per-capita emission level. CCI and EI also render similar outcomes since these policy schemes reward small emitters over the large emitter like Alberta. MI scheme reduces the impact of EI policy since it also takes into account the heterogeneity in the composition of regional economies along with the emissions history and the reward for the efficient emitters. Entitlement-based allocation policies, thus, inevitably benefit some regions at the expense of others.

In contrast, under the NPE policy since emission rights are distributed based on the residual (i.e. equilibrium) level of emissions, no inter-regional transfer of scarcity rents occurs. This significantly raises the political appeal of this policy. From the welfare perspective, model results further indicate that under all six policy schemes, Alberta benefits the most while Québec bears the brunt of the emissions control target. Nonetheless, when reduction in regional GDP is taken into account, Alberta's economy experiences the most contraction relative to the other regional economies. The magnitude of the overall burden, however, varies from one scheme to another.

When considering different criteria of evaluation – such as welfare, household consumption, GDP, dollar purchase of emission permits and others – results corresponding to the set of policy scenarios offer one strikingly consistent yet interesting revelation: allocation scheme based on no prior entitlement of emission right (i.e. the NPE policy) tends to dominate the entitlement-based schemes. In other words, regional economies perform better under the NPE policy, which also has the greatest political appeal. This result is the centerpiece of the qualitative findings derived in this paper, which brings in new insights into the equity-efficiency debate in the exiting literature.

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Tables

Table 2a: Emissions in the BAU (percentage of total emissions in respective categories)

Categories	Alberta	Atlantic Provinces	Ontario	Other Prairie Provinces	Québec	British Columbia and the Territories	National
CO_2 emissions	30.5	8.8	29.5	10.2	12.0	9.0	100
Power generation	40.5	16.6	26.9	13.0	1.3	1.6	100
Industrial	26.9	5.6	36.7	4.5	18.2	8.1	100
Combustion	27.8	7.8	33.6	4.9	17.5	8.5	100
Non-combustion	33.9	1.7	39.1	5.5	15.2	4.6	100
Non-energy (cem, lime)	10.4	1.8	48.1	0.5	26.9	12.3	100
Residential & agricultural	18.5	6.5	44.7	7.4	13.6	9.2	100
Commercial & pub. admin.	16.1	9.7	37.3	9.0	18.2	9.8	100
Oil and gas industries	66.5	2.2	1.5	19.5	0.4	9.9	100
Combustion	76.5	2.9	0.0	10.3	0.0	10.3	100
Fugitives	56.8	1.5	3.0	28.4	0.8	9.5	100
Transportation	17.1	8.6	32.5	9.2	18.3	14.2	100

Source: Statistics Canada and author's calculations

Table 2b: GDP in the BAU (percentage of Canadian GDP)

Alberta	Atlantic Provinces	Ontario	Other Prairie Provinces	Québec	British Columbia and the Territories	National
17.0	6.0	38.4	6.3	19.5	12.9	100

Source: Statistics Canada and author's calculations

Table 2c: Values for behavioral parameters

Parameters	Values
Substitution elasticity	
between value added-energy and intermediate inputs	0.2-0.7
between labour & capital-energy	1.0
between capital & energy	0.2-0.6
between electricity & fossil energy	0.3-0.6
among stationary fossil fuels	0.5-0.9
between other intermediate inputs & mobile fossil fuels	0.3-0.6
among mobile fossil fuels	0.5-0.9
between imports and domestic goods	0.9-4.0
between exports and domestic goods	2.0-4.0
among same industry products*	2.0-4.0

Sources: Various studies

* For multi-products industries

Table 3: Some aggregate variables for Canada (percentage change from benchmark)

	NPE	EBA	EPC	CCI	EI	MI
GDP at market price	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
Disposable income	0.9	0.9	0.8	0.8	0.9	0.9
Household real consumption	0.2	0.2	0.2	0.2	0.2	0.2
Exports	-2.1	-2.0	-2.3	-2.3	-2.2	-2.1
Imports	-2.3	-2.2	-2.5	-2.5	-2.4	-2.3
Investment demand	-3.7	-3.7	-3.6	-3.7	-3.7	-3.7
Industrial CO_2 emissions	-27.7	-27.7	-27.6	-27.6	-27.7	-27.7
Household CO_2 emissions	-12.4	-12.3	-12.8	-12.7	-12.5	-12.4
Total CO_2 emissions	-25.0	-25.0	-25.0	-25.0	-25.0	-25.0

Source: Simulation results

Table 4: Percentage change in GDP at market price

Allocation rule	Alberta	Atlantic Provinces	Ontario	Other Prairie Provinces	Québec	British Columbia and the Territories
NPE	-1.1	-1.1	-0.5	-0.8	-0.4	-0.5
EBA	-1.2	-1.1	-0.4	-0.8	-0.4	-0.5
EPC	-0.9	-1.1	-0.5	-0.7	-0.5	-0.5
CCI	-0.9	-1.0	-0.5	-0.7	-0.5	-0.5
EI	-1.1	-1.1	-0.5	-0.8	-0.4	-0.5
MI	-1.1	-1.1	-0.5	-0.8	-0.4	-0.5

Source: Simulation results

Table 5: Percentage change in welfare

Allocation rule	Alberta	Atlantic Provinces	Ontario	Other Prairie Provinces	Québec	British Columbia and the Territories
NPE	1.7	0.2	0.3	1.5	0.1	0.2
EBA	2.8	0.8	0.1	1.5	-0.1	-0.03
EPC	-2.5	0.0	0.7	0.2	1.4	0.9
CCI	-1.2	-0.6	0.8	-0.1	1.0	0.8
EI	0.7	0.4	0.5	1.1	0.3	0.4
MI	1.1	1.0	0.3	1.6	0.2	0.2

Source: Simulation results

Table 6: Permit revenue ($ ml)

Allocation rule	Alberta	Atlantic Provinces	Ontario	Other Prairie Provinces	Québec	British Columbia and the Territories
NPE	5,934	1,670	7,155	2,100	2,922	2,197
EBA	6,914	1,969	6,446	2,112	2,595	1,981
EPC	2,185	1,606	8,480	1,482	5,154	2,930
CCI	3,341	1,283	8,697	1,354	4,407	2,785
EI	4,989	1,785	7,664	1,899	3,228	2,379
MI	5,329	2,062	7,122	2,151	3,037	2,265

Source: Simulation results

Table 7: Permit Price ($)

Allocation rule	Price in the national market
NPE	49.47
EBA	49.57
EPC	49.15
CCI	49.22
EI	49.40
MI	49.45

Source: Simulation results

Table 8: Dollar purchase of CO_2 permits ($ ml)

Allocation rule	Alberta	Atlantic Provinces	Ontario	Other Prairie Provinces	Québec	British Columbia and the Territories
EBA	-963	-295	718	-9	331	219
EPC	3689	56	-1361	605	-2246	-743
CCI	2549	379	-1570	735	-1496	-596
EI	930	-116	-518	198	-310	-184
MI	598	-390	29	-52	-116	-69

Note: A negative number implies the receipt of permit revenues
Source: Simulation results

Table 9: Percentage change in share of CO_2 permit purchase

Allocation rule	Alberta	Atlantic Provinces	Ontario	Other Prairie Provinces	Québec	British Columbia and the Territories
EBA	-13.9	-15.0	11.1	-0.4	12.7	11.0
EPC	168.9	3.5	-16.1	40.8	-43.6	-25.4
CCI	76.3	29.6	-18.0	54.3	-34.0	-21.4
EI	18.7	-6.5	-6.8	10.4	-9.6	-7.7
MI	11.2	-18.9	0.4	-2.4	-3.8	-3.0

Source: Simulation results

Table 10: Percentage change in total emissions

Allocation rule	Alberta	Atlantic Provinces	Ontario	Other Prairie Provinces	Québec	British Columbia and the Territories
NPE	-35.5	-36.3	-16.6	-25.3	-15.4	-16.7
EBA	-35.4	-36.2	-16.6	-25.3	-15.4	-16.7
EPC	-35.8	-36.2	-16.5	-25.3	-15.3	-16.5
CCI	-35.7	-36.3	-16.5	-25.3	-15.3	-16.6
EI	-35.6	-36.2	-16.6	-25.3	-15.4	-16.6
MI	-35.6	-36.2	-16.6	-25.3	-15.4	-16.7

Source: Simulation results

Table 11: Percentage change in wage

Allocation rule	Alberta	Atlantic Provinces	Ontario	Other Prairie Provinces	Québec	British Columbia and the Territories
NPE	-1.5	-2.1	-1.0	-0.8	-1.0	-1.2
EBA	-1.1	-1.8	-1.0	-0.8	-1.1	-1.3
EPC	-3.3	-2.2	-0.9	-1.4	-0.7	-1.0
CCI	-2.8	-2.4	-0.9	-1.5	-0.8	-1.0
EI	-2.0	-2.0	-0.9	-1.0	-1.0	-1.2
MI	-1.8	-1.8	-1.0	-0.8	-1.0	-1.2

Source: Simulation results

Table 12: Percentage change in labour supply

Allocation rule	Alberta	Atlantic Provinces	Ontario	Other Prairie Provinces	Québec	British Columbia and the Territories
NPE	-1.1	-0.8	-0.4	-0.9	-0.3	-0.4
EBA	-1.3	-0.9	-0.4	-0.9	-0.3	-0.3
EPC	-0.2	-0.8	-0.5	-0.6	-0.6	-0.5
CCI	-0.5	-0.6	-0.5	-0.5	-0.5	-0.5
EI	-0.9	-0.8	-0.4	-0.8	-0.4	-0.4
MI	-0.9	-1.0	-0.4	-0.9	-0.3	-0.4

Source: Simulation results

Table 13a: Total output in Alberta by industry sectors (percentage change)

	NPE	EBA	EPC	CCI	EI	MI
Agriculture	-3.02	-3.65	-0.44	-1.25	-2.39	-2.62
Oil & Gas	0.76	0.39	2.16	1.74	1.12	0.99
Mining	-5.00	-5.35	-3.66	-4.07	-4.66	-4.79
Utilities	-14.97	-14.75	-15.78	-15.52	-15.17	-15.10
Construction	-4.34	-4.54	-3.54	-3.79	-4.14	-4.22
Food	-1.12	-1.64	1.04	0.39	-0.58	-0.80
Other manufact. products	-14.96	-15.28	-13.76	-14.13	-14.66	-14.77
Wood	-6.29	-7.93	0.69	-1.45	-4.60	-5.26
Paper	-35.32	-36.50	-30.31	-31.87	-34.11	-34.58
Printing	-2.15	-2.31	-1.59	-1.77	-2.01	-2.06
Basic chemicals	-45.24	-45.59	-43.91	-44.31	-44.91	-45.04
Plastic & Rubber	-8.82	-9.52	-5.98	-6.86	-8.11	-8.37
Metal & Fabrics	-9.33	-10.06	-6.41	-7.31	-8.60	-8.87
Machineries	-14.00	-15.15	-9.33	-10.80	-12.87	-13.29
Transport equipment	-3.87	-4.82	-0.02	-1.26	-2.92	-3.25
Furniture and related manufact. products	-1.13	-1.91	1.99	0.99	-0.36	-0.63
Trade	-0.42	-0.21	-1.27	-1.02	-0.64	-0.56
Transport	-1.33	-1.45	-0.90	-1.04	-1.23	-1.26
Services	-0.15	0.04	-0.90	-0.67	-0.34	-0.27

Source: Simulation results

Table 13b: Total output in Ontario by industry sectors (percentage change)

	NPE	EBA	EPC	CCI	EI	MI
Agriculture	-0.61	-0.60	-0.60	-0.63	-0.62	-0.61
Oil & Gas	-11.56	-11.46	-11.78	-11.78	-11.64	-11.58
Mining	-8.94	-8.86	-9.03	-9.12	-9.00	-8.92
Utilities	-6.11	-6.19	-5.95	-5.95	-6.06	-6.11
Construction	-3.02	-2.99	-3.11	-3.10	-3.05	-3.03
Food	0.96	0.95	0.98	0.97	0.95	0.95
Other manufact. products	-7.48	-7.39	-7.55	-7.62	-7.53	-7.45
Wood	-1.95	-1.78	-2.16	-2.24	-2.06	-1.94
Paper	-5.41	-5.27	-5.58	-5.67	-5.50	-5.39
Printing	0.34	0.35	0.32	0.31	0.32	0.34
Basic chemicals	-28.36	-28.31	-28.36	-28.44	-28.39	-28.34
Plastic & Rubber	-1.89	-1.54	-2.51	-2.63	-2.14	-1.87
Metal & Fabrics	-3.53	-3.21	-4.17	-4.24	-3.76	-3.52
Machineries	-6.81	-6.49	-7.30	-7.47	-7.04	-6.78
Transport equipment	3.79	4.48	2.32	2.23	3.29	3.79
Furniture and related manufact. products	1.14	1.26	0.98	0.91	1.06	1.15
Trade	0.05	0.01	0.12	0.13	0.07	0.05
Transport	-0.35	-0.35	-0.34	-0.34	-0.35	-0.35
Services	0.27	0.24	0.34	0.35	0.30	0.27

Source: Simulation results

Table 13c: Total output in Québec by industry sectors (percentage change)

	NPE	EBA	EPC	CCI	EI	MI
Agriculture	0.09	0.10	-0.21	-0.08	0.05	0.06
Mining	-7.95	-7.81	-8.92	-8.60	-8.06	-7.96
Utilities	-0.13	-0.20	0.31	0.17	-0.06	-0.11
Construction	-3.08	-3.05	-3.27	-3.20	-3.11	-3.10
Food	0.33	0.32	0.30	0.32	0.33	0.32
Other manufact. products	-7.92	-7.85	-8.53	-8.31	-7.99	-7.95
Wood	-0.43	-0.27	-1.86	-1.31	-0.61	-0.53
Paper	-2.39	-2.21	-4.01	-3.40	-2.58	-2.48
Printing	0.08	0.10	-0.14	-0.05	0.06	0.07
Basic chemicals	-33.24	-33.21	-33.69	-33.51	-33.29	-33.27
Plastic & Rubber	-1.85	-1.61	-3.32	-2.85	-2.06	-1.92
Metal & Fabrics	-3.38	-3.14	-4.89	-4.40	-3.60	-3.46
Machineries	-7.99	-7.49	-11.59	-10.36	-8.46	-8.18
Transport equipment	22.60	23.96	14.80	17.16	21.39	22.20
Furniture and related manufact. products	0.36	0.41	-0.15	0.05	0.30	0.33
Trade	-0.11	-0.17	0.28	0.15	-0.05	-0.09
Transport	-0.39	-0.39	-0.40	-0.40	-0.38	-0.38
Services	-0.04	-0.08	0.24	0.15	0.00	-0.03

Source: Simulation results

Table 14a: Emissions in Alberta by industry sectors (percentage change)

	NPE	EBA	EPC	CCI	EI	MI
Agriculture	-13.56	-14.04	-11.55	-12.18	-13.07	-13.25
Oil & Gas	-11.75	-12.08	-10.50	-10.87	-11.43	-11.55
Mining	-18.27	-18.40	-17.81	-17.94	-18.16	-18.21
Utilities	-57.50	-57.39	-57.93	-57.79	-57.61	-57.58
Construction	-18.53	-18.49	-18.68	-18.63	-18.57	-18.56
Food	-19.80	-20.14	-18.37	-18.79	-19.45	-19.59
Other manufact. products	-35.46	-35.63	-34.81	-35.00	-35.30	-35.36
Wood	-23.42	-24.68	-18.08	-19.71	-22.12	-22.64
Paper	-47.87	-48.75	-44.12	-45.29	-46.97	-47.32
Printing	-17.95	-17.88	-18.29	-18.19	-18.04	-18.01
Basic chemicals	-49.45	-49.77	-48.26	-48.62	-49.16	-49.28
Plastic & Rubber	-21.86	-22.32	-19.99	-20.56	-21.39	-21.57
Metal & Fabrics	-22.27	-22.77	-20.30	-20.90	-21.78	-21.97
Machineries	-26.61	-27.47	-23.14	-24.22	-25.76	-26.08
Transport equipment	-24.39	-24.97	-22.04	-22.79	-23.81	-24.01
Furniture and related manufact. products	-16.70	-17.13	-15.02	-15.56	-16.29	-16.44
Trade	-17.64	-17.30	-18.97	-18.56	-17.98	-17.86
Transport	-8.24	-8.23	-8.30	-8.29	-8.26	-8.25
Services	-16.02	-15.72	-17.19	-16.83	-16.32	-16.22

Source: Simulation results

Table 14b: Emissions in Ontario by industry sectors (percentage change)

	NPE	EBA	EPC	CCI	EI	MI
Agriculture	-9.43	-9.45	-9.34	-9.37	-9.41	-9.42
Oil & Gas	-17.98	-17.90	-18.14	-18.14	-18.04	-17.99
Mining	-18.64	-18.59	-18.63	-18.72	-18.67	-18.61
Utilities	-34.01	-34.10	-33.78	-33.80	-33.94	-34.00
Construction	-8.18	-8.18	-8.18	-8.17	-8.18	-8.19
Food	-14.40	-14.45	-14.24	-14.27	-14.36	-14.39
Other manufact. products	-17.38	-17.34	-17.37	-17.44	-17.40	-17.36
Wood	-11.66	-11.55	-11.75	-11.84	-11.73	-11.64
Paper	-17.60	-17.52	-17.61	-17.71	-17.64	-17.56
Printing	-6.52	-6.55	-6.44	-6.45	-6.50	-6.52
Basic chemicals	-33.78	-33.75	-33.73	-33.81	-33.80	-33.76
Plastic & Rubber	-9.44	-9.15	-9.93	-10.05	-9.64	-9.41
Metal & Fabrics	-10.14	-9.87	-10.66	-10.73	-10.33	-10.13
Machineries	-12.30	-12.03	-12.70	-12.85	-12.49	-12.27
Transport equipment	-5.68	-5.10	-6.92	-7.01	-6.11	-5.68
Furniture and related manufact. products	-9.55	-9.50	-9.57	-9.64	-9.59	-9.54
Trade	-10.27	-10.34	-10.09	-10.10	-10.21	-10.26
Transport	-5.89	-5.92	-5.82	-5.83	-5.87	-5.88
Services	-9.77	-9.84	-9.61	-9.61	-9.71	-9.76

Source: Simulation results

Table 14c: Emissions in Québec by industry sectors (percentage change)

	NPE	EBA	EPC	CCI	EI	MI
Agriculture	-10.25	-10.26	-10.37	-10.30	-10.26	-10.27
Mining	-17.73	-17.63	-18.45	-18.22	-17.80	-17.73
Utilities	-26.76	-26.84	-26.32	-26.45	-26.69	-26.73
Construction	-8.01	-8.01	-8.01	-8.00	-8.01	-8.02
Food	-20.46	-20.51	-20.22	-20.28	-20.41	-20.44
Other manufact. products	-21.21	-21.19	-21.58	-21.44	-21.25	-21.23
Wood	-12.68	-12.57	-13.76	-13.33	-12.81	-12.76
Paper	-18.07	-17.96	-19.20	-18.77	-18.19	-18.13
Printing	-10.06	-10.09	-10.00	-10.00	-10.04	-10.05
Basic chemicals	-43.22	-43.22	-43.51	-43.38	-43.24	-43.24
Plastic & Rubber	-13.96	-13.79	-15.06	-14.71	-14.11	-14.01
Metal & Fabrics	-11.05	-10.86	-12.30	-11.89	-11.23	-11.12
Machineries	-13.97	-13.54	-17.19	-16.08	-14.40	-14.14
Transport equipment	7.78	8.93	1.13	3.15	6.75	7.44
Furniture and related manufact. products	-16.67	-16.68	-16.81	-16.73	-16.67	-16.68
Trade	-14.47	-14.56	-13.90	-14.09	-14.38	-14.44
Transport	-6.93	-6.95	-6.81	-6.85	-6.91	-6.92
Services	-11.73	-11.80	-11.29	-11.43	-11.66	-11.70

Source: Simulation results

Table 15a: Demand for value-added in utilities sector by regions (percentage change)

	NPE	EBA	EPC	CCI	EI	MI
Alberta	-16.97	-16.75	-17.79	-17.53	-17.18	-17.11
Atlantic Provinces	-18.98	-18.88	-18.91	-19.07	-18.91	-18.80
Ontario	-7.02	-7.10	-6.85	-6.85	-6.97	-7.02
Other Prairie Provinces	-15.69	-15.71	-15.89	-15.97	-15.76	-15.66
Québec	-2.81	-2.77	-3.03	-2.95	-2.84	-2.83
British Columbia and the Territories	-1.00	-1.03	-0.90	-0.93	-0.98	-0.99

Source: Simulation results

Table 15b: Demand for value-added in basic chemicals by regions (percentage change)

	NPE	EBA	EPC	CCI	EI	MI
Alberta	-46.47	-46.80	-45.18	-45.57	-46.15	-46.27
Atlantic Provinces	-40.68	-41.03	-40.51	-40.19	-40.78	-41.09
Ontario	-29.15	-29.10	-29.14	-29.22	-29.18	-29.13
Other Prairie Provinces	-20.22	-20.23	-19.30	-19.11	-19.92	-20.30
Québec	-1.47	-1.23	-2.95	-2.48	-1.68	-1.53
British Columbia and the Territories	-40.38	-40.26	-40.78	-40.72	-40.48	-40.42

Source: Simulation results

Table 15c: Demand for value-added in oil & gas by regions (percentage change)

	NPE	EBA	EPC	CCI	EI	MI
Alberta	1.13	0.79	2.42	2.03	1.46	1.34
Atlantic Provinces	11.65	11.43	11.63	11.88	11.54	11.33
Ontario	-11.33	-11.23	-11.53	-11.54	-11.40	-11.34
Other Prairie Provinces	0.93	0.92	1.22	1.27	1.03	0.91
British Columbia and the Territories	-12.14	-12.13	-12.15	-12.16	-12.14	-12.14

Source: Simulation results

Table 16a: Total household consumption in utilities sectors (percentage change)

	NPE	EBA	EPC	CCI	EI	MI
Alberta	-12.51	-11.47	-16.50	-15.26	-13.51	-13.16
Atlantic Province	-12.20	-11.62	-12.26	-12.92	-11.95	-11.41
Ontario	-4.93	-5.16	-4.48	-4.42	-4.76	-4.94
Prairie Provinces	-7.85	-7.85	-9.09	-9.38	-8.26	-7.74
Québec	-0.56	-0.77	0.91	0.42	-0.35	-0.48
British Columbia and the Territories	-2.52	-2.76	-1.73	-1.89	-2.33	-2.45
Canada	-5.02	-5.05	-4.81	-4.90	-4.97	-4.97

Source: Simulation results

Table 16b: Total household consumption in other manufacturing (percentage change)

	NPE	EBA	EPC	CCI	EI	MI
Alberta	1.80	2.98	-2.73	-1.32	0.66	1.06
Atlantic Province	0.22	0.87	0.09	-0.61	0.48	1.08
Ontario	0.38	0.15	0.81	0.88	0.55	0.37
Other Prairie Provinces	1.76	1.77	0.40	0.10	1.31	1.88
Québec	0.03	-0.17	1.42	0.96	0.22	0.10
British Columbia and the Territories	0.15	-0.08	0.94	0.78	0.35	0.22
Canada	0.51	0.52	0.49	0.48	0.50	0.51

Source: Simulation results

Appendix List of equations

Household

$$Y_R = \left(1-\tau_{Y,R}\right)Y_{H,R} + T_{G,R} - ER_R T^W_{G,R}$$

$$Y_{H,R} = w_R L_R + Y_{D,R} + \overline{P}R_R$$

$$Y_{D,R} = \beta_{D,R}\left(1-\tau_{P,R}\right)\sum_j R_{K,R}K_{j,R}$$

$$S_{H,R} = \beta_{S,R}Y_R$$

$$EM_R = \left(1-\beta_{S,R}\right)Y_R$$

$$Y_{NL,R} = EM_R - \left(1-\tau_{Y,R}\right)w_R L_R$$

$$C_R = \alpha_R \frac{\left[\left(1-\tau_{Y,R}\right)w_R H_R + Y_{NL,R}\right]}{P_{C,R}}$$

$$L_R = H_R - \left(1-\alpha_R\right)\frac{\left[\left(1-\tau_{Y,R}\right)w_R H_R + Y_{NL,R}\right]}{\left(1-\tau_{Y,R}\right)w_R}$$

$$P_{C,R} = \frac{1}{A_{C,R}}\left[\left(\theta_{C,R}\right)^{\sigma_{c,R}}\left(P_{HET,R}\right)^{1-\sigma_{c,R}} + \left(1-\theta_{C,R}\right)^{\sigma_{c,R}}\left(P_{HOG,R}\right)^{1-\sigma_{c,R}}\right]^{\frac{1}{1-\sigma_{c,R}}}$$

$$HET_R = \left(A_{C,R}\right)^{\sigma_{c,R}-1}\ C_R\left[\frac{\theta_{C,R}P_{C,R}}{P_{HET,R}}\right]^{\sigma_{c,R}}$$

$$HOG_R = \left(A_{C,R}\right)^{\sigma_{c,R}-1}\ C_R\left[\frac{\left(1-\theta_{C,R}\right)P_{C,R}}{P_{HOG,R}}\right]^{\sigma_{c,R}}$$

$$P_{HET,R} = \frac{1}{A_{HET,R}}\left[\sum_i\left(\theta_{HET,i,R}\right)^{\sigma_{HET,R}}\left(P_{HET,i,R}\right)^{1-\sigma_{HET,R}}\right]^{\frac{1}{1-\sigma_{HET,R}}}$$

$$HET_{i,R} = \left(A_{HET,R}\right)^{\sigma_{HET,R}-1}\ HET_R\left[\frac{\theta_{HET,i,R}P_{HET,R}}{P_{HET,i,R}}\right]^{\sigma_{HET,R}}$$

$$P_{HOG,R} = \frac{1}{A_{HOG,R}}\left[\sum_i\left(\theta_{HOG,i,R}\right)^{\sigma_{HOG,R}}\left(P_{HOG,i,R}\right)^{1-\sigma_{HOG,R}}\right]^{\frac{1}{1-\sigma_{HOG,R}}}$$

$$HOG_{i,R} = \left(A_{HOG,R}\right)^{\sigma_{HOG,R}-1}\ HOG_R\left[\frac{\theta_{HOG,i,R}P_{HOG,R}}{P_{HOG,i,R}}\right]^{\sigma_{HOG,R}}$$

Firms

$$P_{\overline{Q},j,R} = \frac{1}{A_{Q,j,R}}\left[\left(\varphi_{j,R}\right)^{\sigma_{Q,j,R}}\left(P_{X,j,R}\right)^{1-\sigma_{Q,j,R}} + \left(1-\varphi_{j,R}\right)^{\sigma_{Q,j,R}}\left(P_{M,j,R}\right)^{1-\sigma_{Q,j,R}}\right]^{\frac{1}{1-\sigma_{Q,j,R}}}$$

$$X_{j,R} = \left(A_{Q,j,R}\right)^{\sigma_{Q,j,R}-1}\ Q_{j,R}\left[\frac{\varphi_{j,R}P_{\overline{Q},j,R}}{P_{X,j,R}}\right]^{\sigma_{Q,j,R}}$$

$$M_{j,R} = \left(A_{Q,j,R}\right)^{\sigma_{Q,j,R}-1} \; Q_{j,R} \; \left[\frac{\left(1-\varphi_{j,R}\right)P_{\bar{Q},j,R}}{P_{M,j,R}}\right]^{\sigma_{Q,j,R}}$$

$$P_{X,j,R} = \frac{1}{A_{X,j,R}}\left[\frac{\left(P_{KE,j,R}\right)^{\varphi_{X,j,R}}}{\varphi_{X,j,R}}\frac{\left(w_R\right)^{1-\varphi_{X,j,R}}}{\left(1-\varphi_{X,j,R}\right)}\right]$$

$$KE_{j,R} = \varphi_{X,j,R}\,\frac{P_{X,j,R}\;X_{j,R}}{P_{KE,j,R}}$$

$$L^D_{j,R} = \left(1-\varphi_{X,j,R}\right)\frac{P_{X,j,R}\;X_{j,R}}{w_R}$$

$$P_{KE,j,R} = \frac{1}{A_{KE,j,R}}\left[\left(\varphi_{KE,j,R}\right)^{\sigma_{KE,j,R}}\left(R_{K,R}\right)^{1-\sigma_{KE,j,R}} + \left(1-\varphi_{KE,j,R}\right)^{\sigma_{KE,j,R}}\left(P_{EST,j,R}\right)^{1-\sigma_{KE,j,R}}\right]^{\frac{1}{1-\sigma_{KE,j,R}}}$$

$$K^D_{j,R} = \left(A_{KE,j,R}\right)^{\sigma_{KE,j,R}-1} \; KE_{j,R} \; \left[\frac{\varphi_{KE,j,R}P_{KE,j,R}}{R_{K,R}}\right]^{\sigma_{KE,j,R}}$$

$$EST_{j,R} = \left(A_{KE,j,R}\right)^{\sigma_{KE,j,R}-1} \; KE_{j,R} \; \left[\frac{\left(1-\varphi_{KE,j,R}\right)P_{KE,j,R}}{P_{EST,j,R}}\right]^{\sigma_{KE,j,R}}$$

$$P_{EST,j,R} = \frac{1}{A_{EST,j,R}}\left[\left(\varphi_{EST,j,R}\right)^{\sigma_{EST,j,R}}\left(P_{ESF,j,R}\right)^{1-\sigma_{EST,j,R}} + \left(1-\varphi_{EST,j,R}\right)^{\sigma_{EST,j,R}}\left(P_{ELEC,j,R}\right)^{1-\sigma_{EST,j,R}}\right]^{\frac{1}{1-\sigma_{EST,j,R}}}$$

$$ESF_{j,R} = \left(A_{EST,j,R}\right)^{\sigma_{EST,j,R}-1} \; EST_{j,R} \; \left[\frac{\varphi_{EST,j,R}P_{EST,j,R}}{P_{ESF,j,R}}\right]^{\sigma_{EST,j,R}}$$

$$ELEC_{j,R} = \left(A_{EST,j,R}\right)^{\sigma_{EST,j,R}-1} \; EST_{j,R} \; \left[\frac{\left(1-\varphi_{EST,j,R}\right)P_{EST,j,R}}{P_{ELEC,j,R}}\right]^{\sigma_{EST,j,R}}$$

$$P_{ESF,j,R} = \frac{1}{A_{ESF,j,R}}\left[\sum_{i\in VS_{i,j}}\left(\varphi_{ESF,i,j,R}\right)^{\sigma_{ESF,j,R}}\left(P_{VS,i,j,R}\right)^{1-\sigma_{ESF,j,R}}\right]^{\frac{1}{1-\sigma_{ESF,j,R}}}$$

$$VS_{i,j,R} = \left(A_{ESF,j,R}\right)^{\sigma_{ESF,j,R}-1} \; ESF_{j,R} \; \left[\frac{\varphi_{ESF,i,j,R}P_{ESF,j,R}}{P_{VS,i,j,R}}\right]^{\sigma_{ESF,j,R}}$$

$$P_{M,j,R} = \frac{1}{A_{M,j,R}}\left[\left(\varphi_{M,j,R}\right)^{\sigma_{M,j,R}}\left(P_{EMF,j,R}\right)^{1-\sigma_{M,j,R}} + \left(1-\varphi_{M,j,R}\right)^{\sigma_{M,j,R}}\left(P_{MATT,j,R}\right)^{1-\sigma_{M,j,R}}\right]^{\frac{1}{1-\sigma_{M,j,R}}}$$

$$EMF_{j,R} = \left(A_{M,j,R}\right)^{\sigma_{M,j,R}-1} \; M_{j,R} \; \left[\frac{\varphi_{M,j,R}P_{M,j,R}}{P_{EMF,j,R}}\right]^{\sigma_{M,j,R}}$$

$$MATT_{j,R} = \left(A_{M,j,R}\right)^{\sigma_{M,j,R}-1} \; M_{j,R} \; \left[\frac{\left(1-\varphi_{M,j,R}\right)P_{M,j,R}}{P_{MATT,j,R}}\right]^{\sigma_{M,j,R}}$$

$$P_{EMF,j,R} = \frac{1}{A_{EMF,j,R}} \left[\sum_{i \in VM_{i,j}} \left(\varphi_{EMF,i,j,R}\right)^{\sigma_{EMF,j,R}} \left(P_{VM,i,j,R}\right)^{1-\sigma_{EMF,j,R}} \right]^{\frac{1}{1-\sigma_{EMF,j,R}}}$$

$$VM_{i,j,R} = \left(A_{EMF,j,R}\right)^{\sigma_{EMF,j,R}-1} \; EMF_{j,R} \left[\frac{\varphi_{EMF,i,j,R} P_{EMF,j,R}}{P_{VM,i,j,R}} \right]^{\sigma_{EMF,j,R}}$$

$$P_{MATT,j,R} = \sum_{i \in VMATT_{i,j}} \Upsilon_{i,j,R} P_{VMATT,i,j,R}$$

$$VMATT_{i,j,R} = \Upsilon_{i,j,R} \; MATT_{i,j,R}$$

$$S_{Q,R} = \beta_{Q,R}\left(1-\tau_{P,R}\right) \sum_{j} R_{K,j,R} K_{j,R}$$

Government

$$Y_{G,R} = \tau_{Y,R} Y_{H,R} + \tau_{D,R} \sum_{j} R_{K,R} K_{j,R} + \sum_{i} \tau_{C,i,R} P_{\bar{C},i,R} C_{i,R} + \sum_{j} \tau_{Q,j,R} P_{\bar{Q},j,R} Q_{j,R}$$
$$+ \sum_{i} \tau_{I,i,R} P_{\bar{I},i,R} I_{i,R} + \sum_{i} ER_{R} \tau_{IM,i,R} P^{W}_{C,i} C^{IM}_{ROW,i,R}$$

$$S_{G,R} = Y_{G,R} - \sum_{i} P_{C,i,R} C_{G,i,R} - T_{G,R}$$

Trade – International and Regional

$$P_{\bar{C},i,R} = \frac{1}{A_{m,i,R}} \left[\left(\kappa_{i,R}\right)^{\sigma_{m,i,R}} \left(P^{D}_{C,i,R}\right)^{1-\sigma_{m,i,R}} + \left(1-\kappa_{i,R}\right)^{\sigma_{m,i,R}} \left(P^{IM}_{C,i,R}\right)^{1-\sigma_{m,i,R}} \right]^{\frac{1}{1-\sigma_{m,i,R}}}$$

$$C^{D}_{i,R} = \left(A_{m,i,R}\right)^{\sigma_{m,i,R}-1} C_{i,R} \left(\frac{\kappa_{i,R} P_{\bar{C},i,R}}{P^{D}_{C,i,R}} \right)^{\sigma_{m,i,R}}$$

$$C^{IM}_{i,R} = \left(A_{m,i,R}\right)^{\sigma_{m,i,R}-1} C_{i,R} \left(\frac{\left(1-\kappa_{i,R}\right) P_{\bar{C},i,R}}{P^{IM}_{C,i,R}} \right)^{\sigma_{m,i,R}}$$

$$P^{IM}_{C,i,R} = \frac{1}{A_{IM,i,R}} \left[\left(\kappa_{IM,i,R}\right)^{\sigma_{IM,i,R}} \left(P^{IM}_{ROR,i,R}\right)^{1-\sigma_{IM,i,R}} + \left(1-\kappa_{IM,i,R}\right)^{\sigma_{IM,i,R}} \left(P^{IM}_{ROW,i,R}\right)^{1-\sigma_{IM,i,R}} \right]^{\frac{1}{1-\sigma_{IM,i,R}}}$$

$$C^{IM}_{ROR,i,R} = \left(A_{IM,i,R}\right)^{\sigma_{IM,i,R}-1} C^{IM}_{i,R} \left(\frac{\kappa_{IM,i,R} P^{IM}_{C,i,R}}{P^{IM}_{ROR,i,R}} \right)^{\sigma_{IM,i,R}}$$

$$C^{IM}_{ROW,i,R} = \left(A_{IM,i,R}\right)^{\sigma_{IM,i,R}-1} C^{IM}_{i,R} \left(\frac{\left(1-\kappa_{IM,i,R}\right) P^{IM}_{C,i,R}}{P^{IM}_{ROW,i,R}} \right)^{\sigma_{IM,i,R}}$$

$$P^{IM}_{ROR,i,R} = \frac{1}{A_{IMR,i,R}} \left[\sum_{P} \left(\kappa_{IMR,i,P,R}\right)^{\sigma_{IMR,i,R}} \left(P^{IM}_{ROR,i,P,R}\right)^{1-\sigma_{IMR,i,R}} \right]^{\frac{1}{1-\sigma_{IMR,i,R}}}$$

$$C^{IM}_{ROR,i,P,R} = \left(A_{IMR,i,R}\right)^{\sigma_{IMR,i,R}-1} C^{IM}_{ROR,i,R} \left(\frac{\kappa_{IMR,i,P,R} P^{IM}_{ROR,i,R}}{P^{IM}_{ROR,i,P,R}} \right)^{\sigma_{IMR,i,R}}$$

$$P_{EX,j,R} = \frac{1}{A_{e,j,R}}\left[\left(\eta_{j,R}\right)^{-\sigma_{x,j,R}}\left(P_{\bar{Q},j,R}\right)^{1+\sigma_{x,j,R}} + \left(1-\eta_{j,R}\right)^{-\sigma_{x,j,R}}\left(P^{EX}_{\bar{Q},j,R}\right)^{1+\sigma_{x,j,R}}\right]^{\frac{1}{1+\sigma_{x,j,R}}}$$

$$Q^{D}_{j,R} = \left(A_{e,j,R}\right)^{-1-\sigma_{x,j,R}} EX_{j,R}\left(\frac{P_{\bar{Q},j,R}}{\eta_{j,R}P_{EX,j,R}}\right)^{\sigma_{x,j,R}}$$

$$Q^{EX}_{j,R} = \left(A_{e,j,R}\right)^{-1-\sigma_{x,j,R}} EX_{j,R}\left(\frac{P^{EX}_{\bar{Q},j,R}}{\left(1-\eta_{j,R}\right)P_{EX,j,R}}\right)^{\sigma_{x,j,R}}$$

$$P^{EX}_{\bar{Q},j,R} = \frac{1}{A_{EX,j,R}}\left[\left(\eta_{EX,j,R}\right)^{-\sigma_{EX,j,R}}\left(P^{EX}_{ROR,j,R}\right)^{1+\sigma_{EX,j,R}} + \left(1-\eta_{EX,j,R}\right)^{-\sigma_{EX,j,R}}\left(P^{EX}_{ROW,j,R}\right)^{1+\sigma_{EX,j,R}}\right]^{\frac{1}{1+\sigma_{EX,j,R}}}$$

$$Q^{EX}_{ROR,j,R} = \left(A_{EX,j,R}\right)^{-1-\sigma_{EX,j,R}} Q^{EX}_{j,R}\left(\frac{P^{EX}_{ROR,j,R}}{\eta_{EX,j,R}P^{EX}_{\bar{Q},j,R}}\right)^{\sigma_{EX,j,R}}$$

$$Q^{EX}_{ROW,j,R} = \left(A_{EX,j,R}\right)^{-1-\sigma_{EX,j,R}} Q^{EX}_{j,R}\left(\frac{P^{EX}_{ROW,j,R}}{\left(1-\eta_{EX,j,R}\right)P^{EX}_{\bar{Q},j,R}}\right)^{\sigma_{EX,j,R}}$$

$$P^{EX}_{ROR,j,R} = \frac{1}{A_{EXR,j,R}}\left[\sum_{P}\left(\eta_{EXR,j,P,R}\right)^{-\sigma_{EXR,j,R}}\left(P^{EX}_{ROR,j,P,R}\right)^{1+\sigma_{EXR,j,R}}\right]^{\frac{1}{1+\sigma_{EXR,j,R}}}$$

$$Q^{EX}_{ROR,j,P,R} = \left(A_{EXR,j,R}\right)^{-1-\sigma_{EXR,j,R}} Q^{EX}_{ROR,j,R}\left(\frac{P^{EX}_{ROR,j,P,R}}{\eta_{EXR,j,P,R}P^{EX}_{ROR,j,R}}\right)^{\sigma_{EXR,j,R}}$$

Capital account

$$S_{F,R} = \sum_{i} P^{W}_{C,i}C^{IM}_{ROW,i,R} - \sum_{j} P^{W}_{\bar{Q},j}Q^{EX}_{ROW,j,R} + T^{W}_{G,R}$$

$$S_{F} = \sum_{R} ER_{R}S_{F,R}$$

Demand for investment commodities and total demand

$$P_{I,i,R}I_{i,R} = \beta_{I,R}\left(S_{F} + S_{D}\right)$$

$$S_{D} = \sum_{R}\left(S_{H,R} + S_{G,R} + S_{Q,R}\right)$$

$$C^{D}_{i,R} = C_{i,R} + C_{G,i,R} + I_{i,R} + \sum_{j} V_{i,j,R}$$

Prices

$$P_{C,i,R} = \left[P_{\bar{C},i,R} + \overline{P}\ \ \xi_{H,i,R}\right]\left(1+\tau_{C,i,R}\right)$$

$$P_{\bar{Q},j,R} = P_{Q,j,R}\left(1-\tau_{Q,j,R}\right)$$

$$P_{I,i,R} = P_{\bar{I},i,R}\left(1+\tau_{I,i,R}\right)$$

$$P_{V,i,j,R} = \left[P_{\bar{C},i,R} + \overline{P}\ \ \xi_{\cdot\cdot Q,i,j,R}\right]$$

$$P^{EX}_{ROR,j,P,R} = P^{IM}_{ROR,i,P,R}$$

$$Q^{EX}_{ROR,j,P,R} = C^{IM}_{ROR,i,P,R}$$

$$P^{IM}_{ROW,i,R} = ER_R \left(1 + \tau_{IM,i,R}\right) P^{W}_{C,i}$$

$$P^{EX}_{ROW,j,R} = ER_R P^{W}_{\overline{Q},j}$$

$$\overline{P}_R = \overline{P}$$

Equilibrium conditions

$$C^{D}_{i,R} = Q^{D}_{j,R}$$

$$\sum_j L^{D}_{j,R} = L_R$$

$$\sum_j K^{D}_{j,R} = \overline{K}_R$$

$$\sum_R E_R = \overline{E}$$

Emissions

$$E_{H,R} = \sum_i \left(\xi_{H,i,R} C_{i,R}\right)$$

$$E_{Q,j,R} = \sum_i \left(\xi_{Q,i,j,R} V_{i,j,R}\right)$$

$$E_R = E_{H,R} + \sum_j E_{Q,j,R}$$

$$E = \sum_R E_R$$

$$PR_R = \overline{P} R_R$$

Emission based allocation of permits:

$$R_R = \Phi_{EBA,R} \ \overline{E}$$

Allocation based on emissions per capita:

$$R_R = \Phi_{Pop,R} \ \overline{E}$$

Allocation based on converging carbon intensity:

$$R_R = \upsilon \ \Phi_{CCI} \ GDP_R$$

$$\sum_R R_R = \overline{E}$$

$$\Phi_{CCI} = \frac{\underline{E}_{R,Base}}{GDP_{R,Base}} = \min\left\{\frac{E_{R,Base}}{GDP_{R,Base}}\right\} \qquad \text{for} \quad R = 1, 2, 3, \ldots$$

$$GDP_R = w_R \sum_j L^{D}_{j,R} + R_{K,R} \sum_j K^{D}_{j,R}$$

Allocation based on efficiency index:

$$R_R = \upsilon \ E_{R,Base} \ \left(1 - \mathrm{GAP} * \Phi_{EI,R}\right) \qquad \text{where} \ \mathrm{GAP} = \frac{\left(\sum_R E_R - \overline{E}\right)\Phi_{EI,R}}{\sum_R E_R}$$

$$\sum_R R_R = \overline{E}$$

$$\Phi_{EI,R} = \frac{E_{R,Base} \big/ GDP_{R,Base}}{\sum_R E_{R,Base} \Big/ \sum_R GDP_{R,Base}}$$

Allocation based on multi-criteria index:

$$R_R = \upsilon\, E_{R,Base}\ \left(1 - \text{GAP} * \Phi_{MI,R}\right) \qquad \text{where } \text{GAP} = \frac{\left(\sum_R E_R - \overline{E}\right)\Phi_{MI,R}}{\sum_R E_R}$$

$$\sum_R R_R = \overline{E}$$

$$\Phi_{MI,R} = \left[\omega_A \left(A_R \Big/ \sum_R A_R \right) + \omega_B \left(B_R \Big/ \sum_R B_R \right) + \omega_C \left(C_R \Big/ \sum_R C_R \right) + \omega_D \left(D_R \Big/ \sum_R D_R \right)\right]$$

Allocation based on no prior entitlement:

$$R_R = E_{R,Residual}$$

List of variables (subscript R in any variable denotes a region)

Y_R : aggregate disposable income of the representative household in region R

$Y_{H,R}$: gross aggregate income of household

$T_{G,R}$: government transfer to region R household

$T_{G,R}^{W}$: government transfer to rest of the world by region R

w_R : net rate of return to labour (i.e. wage rate net of (payroll) tax)

L_R : aggregate supply of labour

$Y_{D,R}$: disposable (i.e. net of tax) dividend income

$\overline{PR}_R$: permit revenue received by the household

$R_{K,R}$: gross rate of return to capital (i.e. gross rate of return from investment in capital)

$S_{H,R}$: household savings

EM_R : total household expenditure

$Y_{NL,R}$: non-labour income

C_R : composite consumption

$P_{C,R}$: index price of aggregate consumption bundle

HET_R : composite of (non-mobile) energy goods

$P_{HET,R}$: index price of composite (non-mobile) energy goods

$HET_{i,R}$: quantity of (non-mobile) energy good i

$P_{HET,i,R}$: price of (non-mobile) energy good i

HOG_R : composite of materials-mobile energy commodities (i.e. other household goods)

$P_{HOG,R}$: index price of composite materials-mobile energy commodities

$HOG_{i,R}$: quantity of materials-mobile energy good i

$P_{HOG,i,R}$: price of materials-mobile energy good i

$Q_{j,R}$: quantity of composite output produced by firm j

$P_{\bar{Q},j,R}$: net of tax price of output of firm j

$P_{Q,j,R}$: gross of tax price of output j

$X_{j,R}$: quantity of composite capital-labour-energy input of industry j

$P_{X,j,R}$: index price of composite capital-labour-energy input used in industry j

$M_{j,R}$: quantity of aggregate material-mobile factor used in firm j

$P_{M,j,R}$: index price of material-mobile factor used in firm j

$KE_{j,R}$: quantity of composite capital-energy factor used in industry j

$P_{KE,j,R}$: index price of capital-energy factor used in industry j

$L^{D}_{j,R}$: quantity of labour demanded in firm j

$EST_{j,R}$: quantity of composite of energy factors used in industry j

$P_{EST,j,R}$: index price of composite of energy factors used in industry j

$K^{D}_{j,R}$: quantity of capital demanded in firm j

$ESF_{j,R}$: quantity of composite of non-mobile energy factors used in industry j

$P_{ESF,j,R}$: index price of composite of non-mobile energy factors used in industry j

$ELEC_{j,R}$: amount of electricity input used in firm j

$P_{ELEC,j,R}$: price of electricity input used in firm j

$VS_{i,j,R}$: quantity of non-mobile factor i used as intermediate input in industry j

$P_{VS,i,j,R}$: price of non-mobile factor i used as intermediate input in industry j

$EMF_{j,R}$: quantity of composite of mobile energy factors used in firm j

$P_{EMF,j,R}$: index price of composite of mobile energy factors used in firm j

$MATT_{j,R}$: quantity of composite of material factors used in industry j

$P_{MATT,j,R}$: index price of composite of material factors used in industry j

$VM_{i,j,R}$: quantity of mobile factor i used as intermediate input in firm j

$P_{VM,i,j,R}$: price of mobile factor i used as intermediate input in firm j

$VMATT_{i,j,R}$: quantity of material factor i used as intermediate input in industry j

$P_{VMATT,i,j,R}$: price of material factor i used as intermediate input in industry j

$S_{Q,R}$: corporate savings by firm j

$Y_{G,R}$: government income

$S_{G,R}$: government savings

$I_{i,R}$: quantity of investment of good i

$P_{\bar{I},i,R}$: net of tax price of investment of good i

$C_{G,i,R}$: government consumption of good i

$P_{C,i,R}$: gross of tax price of good i

$C_{i,R}$: quantity of composite of good i

$P_{\overline{C},i,R}$: net of tax price of good i
$C^{D}_{i,R}$: quantity consumed of good i sourced from domestic market
$P^{D}_{C,i,R}$: index price of good i sourced from domestic market
$C^{IM}_{i,R}$: quantity of composite of total imports of good i
$P^{IM}_{C,i,R}$: index price of composite of total imports of good i
$C^{IM}_{ROR,i,R}$: quantity of composite imports of good i sourced from rest of the region (ROR)
$P^{IM}_{ROR,i,R}$: index price of composite imports of good i sourced from ROR
$C^{IM}_{ROW,i,R}$: quantity of composite imports of good i sourced from rest of the world (ROW)
$P^{IM}_{ROW,i,R}$: index price of composite imports of good i sourced from ROW
$C^{IM}_{ROR,i,P,R}$: quantity imported of good i form ROR
$P^{IM}_{ROR,i,P,R}$: price of imported good i form ROR
$EX_{j,R}$: quantity of composite of total exports from industry j
$P_{EX,j,R}$: index price of composite of total exports from industry j
$Q^{D}_{j,R}$: quantity supplied to domestic market from firm j
$Q^{EX}_{j,R}$: quantity supplied to export markets from industry j
$P^{EX}_{\overline{Q},j,R}$: index price of export composite from industry j
$Q^{EX}_{ROR,j,R}$: quantity supplied to composite of rest of the region (ROR) export markets from firm j
$P^{EX}_{ROR,j,R}$: index price of export composite for ROR markets from firm j
$Q^{EX}_{ROW,j,R}$: quantity supplied to composite of rest of the world (ROW) export markets from industry j
$P^{EX}_{ROW,j,R}$: index price of export composite for ROW from industry j
$Q^{EX}_{ROR,j,P,R}$: quantity supplied to ROR export market from firm j
$P^{EX}_{ROR,j,P,R}$: price of ROR export from firm j
$S_{F,R}$: foreign savings in region R
S_{F} : national foreign savings
$P_{I,i,R}$: gross of tax price of investment of good i
S_{D} : total domestic savings
$V_{i,j,R}$: quantity of factor i used as intermediate input in firm j
$P_{V,i,j,R}$: price of good i used as intermediate good in industry j
$\overline{P}$: endogenously determined (at the national emission permit market) price of emission permit
$\overline{P}_{R}$: price of permit in region R
$E_{H,R}$: household emissions in region R
$E_{Q,j,R}$: industrial (process) emissions produced from good j in region R
E_{R} : total emissions in region R

E : national emissions

R_R : total emission rights received by region R

List of parameters (subscript R in any variable denotes a region)

ER_R : exchange rate (price of foreign currency in terms of domestic currency); model numéraire

$\beta_{D,R}$: household share of total dividend income

$\tau_{Y,R}$: non-dividend income tax rate in region R

$\tau_{P,R}$: tax rate on dividend income

$\beta_{S,R}$: household marginal propensity to save

α_R : share of expenditure on aggregate consumption

H_R : total time endowment

$\xi_{H,i,R}$: emission factor of good i used in household consumption in region R

$\xi_{Q,i,j,R}$: emission factor of good i used as intermediate (in industry j) input in production in region R

$A_{C,R}$: shift parameter in the consumption aggregator function

$\theta_{C,R}$: share parameter in the consumption aggregator function

$\sigma_{c,R}$: elasticity of substitution between consumption goods

$A_{HET,R}$: shift parameter in the energy composite good

$\theta_{HET,i,R}$: share parameter for energy good i

$\sigma_{HET,R}$: elasticity of substitution among energy goods

$A_{HOG,R}$: shift parameter in the non-energy composite commodity

$\theta_{HOG,i,R}$: share parameter for non-energy good i

$\sigma_{HOG,R}$: elasticity of substitution among non-energy commodities

$\beta_{Q,R}$: corporate marginal propensity to save

$\tau_{Q,j,R}$: rate of production tax on output of good j

$A_{Q,j,R}$: shift parameter in the production aggregator function of firm j

$\varphi_{j,R}$: share parameter in the production aggregator function of firm j

$\sigma_{Q,j,R}$: elasticity of substitution between inputs used to produce composite output of firm j

$A_{X,j,R}$: shift parameter in capital-energy composite function of industry j

$\varphi_{X,j,R}$: share parameter in capital-energy composite function of industry j

$A_{KE,j,R}$: shift parameter in energy composite function of firm j

$\varphi_{KE,j,R}$: share parameter in energy composite function of firm j

$\sigma_{KE,j,R}$: elasticity of substitution between capital and composite of energy inputs of firm j

$A_{EST,j,R}$: shift parameter in aggregator function of non-mobile energy and electricity inputs of industry j

$\varphi_{EST,j,R}$: share parameter in aggregator function of non-mobile energy and electricity inputs of industry j

$\sigma_{EST,j,R}$: elasticity of substitution between electricity and composite of non-mobile energy inputs used in industry j

$A_{ESF,j,R}$: shift parameter in aggregator function of non-mobile energy inputs of firm j

$\varphi_{ESF,j,R}$: share parameter in aggregator function of non-mobile energy inputs of firm j

$\sigma_{ESF,j,R}$: elasticity of substitution among non-mobile energy inputs used in firm j

$A_{M,j,R}$: shift parameter in aggregator function of material inputs and mobile energy factors used in industry j

$\varphi_{M,j,R}$: share parameter in aggregator function of material inputs and mobile energy factors used in industry j

$\sigma_{M,j,R}$: elasticity of substitution between composite of mobile energy factors and material inputs used in industry j

$A_{EMF,j,R}$: shift parameter in aggregator function of mobile energy inputs of firm j

$\varphi_{EMF,j,R}$: share parameter in aggregator function of mobile energy inputs of firm j

$\sigma_{EMF,j,R}$: elasticity of substitution among mobile energy inputs used in firm j

$\Upsilon_{i,j,R}$: Leontief co-efficient for composite of material inputs used in industry j

$P^{W}_{C,i}$: net of tariff price of imported good i in foreign currency units

$P^{W}_{\bar{Q},j}$: price of exported good j in world market in foreign currency units

$\tau_{C,i,R}$: tax rate on consumption good i

$\tau_{I,i,R}$: tax rate on investment of good i

$\tau_{IM,i,R}$: import tariff rate on good i

$A_{m,i,R}$: shift parameter in total import aggregator function for good i

$\kappa_{i,R}$: share parameter in total import aggregator function for good i

$\sigma_{m,i,R}$: elasticity of substitution between domestic and import demands for good i

$A_{IM,i,R}$: shift parameter in aggregator function for import composite for good i

$\kappa_{IM,i,R}$: share parameter in aggregator function for import composite for good i

$\sigma_{IM,i,R}$: elasticity of substitution between rest of the region (ROR) and rest of the world (ROW) import demands for good i

$A_{IMR,i,R}$: shift parameter in aggregator function for regional import composite for good i

$\kappa_{IMR,i,P,R}$: share parameter in aggregator function for regional import composite for good i

$\sigma_{IMR,i,R}$: elasticity of substitution for imports sourced from ROR markets for good i

$A_{e,j,R}$: shift parameter in total export aggregator function from firm j

$\eta_{j,R}$: share parameter in total export aggregator function from firm j

$\sigma_{e,j,R}$: elasticity of substitution between domestic and export supplies from firm j

$A_{EX,j,R}$: shift parameter in aggregator function for export composite from industry j

$\eta_{EX,j,R}$: share parameter in aggregator function for export composite from industry j

$\sigma_{EX,j,R}$: elasticity of substitution between rest of the region (ROR) and rest of the world (ROW) export supplies from industry j

$A_{EXR,j,R}$: shift parameter in aggregator function for regional export composite from firm j

$\eta_{EXR,j,P,R}$: share parameter in aggregator function for regional export composite from firm j

$\sigma_{EXR,j,R}$: elasticity of substitution for exports among ROR from firm j

$\beta_{I,R}$: region R's share of national savings

$\overline{K}_R$: exogenous capital stock

$\overline{E}$: exogenous national emissions target

$\Phi_{EBA,R}$: parameter reflecting emission based allocation

$\Phi_{Pop,R}$: parameter reflecting allocation based on per capita emissions

Φ_{CCI}: parameter reflecting allocation based on converging carbon intensity

$E_{R,Base}$: level of regional emissions the base period

Φ_{EI}: parameter reflecting allocation based on efficiency index

Φ_{MI}: parameter reflecting allocation based on multi-criteria index