Regional, sectoral and temporal differences in carbon leakage

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Contributed paper prepared for presentation at the
57th AARES Annual Conference, Sydney,
New South Wales, 5th-8th February, 2013

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Abstract

While greenhouse gas emissions trading schemes, taxes and other measures have already been implemented or are proposed in many countries and regions, global action to mitigate climate change remains insufficient. A major concern in many countries is that actions taken alone, or even in a limited coalition of countries, might result in competitive disadvantage to firms in emissions-intensive, trade-exposed industries. Additionally, this might results in emissions leakage, reducing environmental effectiveness.

The problem of emissions leakage has been extensively studied in the case of mitigation by individual or coalitions of developed countries, most often, using comparative static partial or general equilibrium models. In this paper we use a multiregional dynamic general equilibrium model to study the imposition of harmonised carbon taxes on industrial and energy greenhouse gas emissions in OECD countries and in China. This tax rate is increasing over time. We find that the overall rate of emissions leakage is very low and decreases over time. We also find significant differences between regions in the marginal rates of leakage with respect to their participation (or not) in the carbon-pricing coalition. Differences in leakage rates and their change over time can be related to differences in energy systems, general economic structure and growth rates.

Keywords: carbon price, emissions, leakage, general equilibrium

Introduction

Domestic policies, including carbon taxes and emissions trading schemes (ETS), have been implemented at national or sub-national levels in many developed countries (e.g. European Union, New Zealand, Australia, Korea, in California and in the north-eastern United States). Having already measures that have substantially reduced energy intensities, China is trialling emissions trading schemes and plans to introduce a national scheme in 2015. Many other developing countries are also taking or considering actions to reduce emissions or their rate of increase. However, at a global level, current and planned policies still appear insufficient to be compatible with the internationally agreed objective of limiting the increase in global mean temperature to 2°C (UNFCCC, 2010).

There is much economic evidence to suggest that globally, the benefits of a more rapid response to the problem of climate change would outweigh the costs (Stern, 2007). However, action is made much more difficult by the facts that many of the costs will be incurred in the short and medium term by individual citizens, firms and governments, while most of the benefits will accrue in the distant future and are non-excludable. To further complicate matters, countries differ greatly in the degree of their historic responsibility for the problem and in their economic and institutional capacities to respond. Thus, there are strong incentives for some countries to free-ride or more particularly, to defer actions until agreement can be reached on a broader and more coordinated approach.[1]

Reluctance to undertake unilateral or even multilateral mitigation actions reflect not only concerns about economic costs and the problem of free-riding, but also concerns that environmental effectiveness may be undermined by the phenomenon of carbon leakage. Simply defined, carbon leakage occurs when actions taken by one country to reduce emissions result in emissions increases in other countries. This problem is most tangible as it relates to emissions-intensive, trade-exposed (EITE) industries. The fear is that climate policies implemented by one (or several) countries will cause production to shift to other countries. Measures to avoid or reduce any comparative disadvantage suffered by such producers are widespread. There are prominent examples in the New Zealand, Australian, and European Union ETS. A large literature, some of which we review below, addresses competitiveness impacts of climate policies and the associated issue of carbon leakage. It includes both theoretical contributions and large-scale modelling studies in partial or general equilibrium frameworks.

In this paper, we provide a quantification of leakage rates that differs in several respects from the many earlier estimates. Firstly, we employ an intertemporal general equilibrium trade model that has a sophisticated representation of capital stocks and explicitly distinguishes fossil from carbon-free electricity generation. The dynamic features of our model are better suited to modelling economic adjustment processes than the comparative static or even recursive dynamic models used in most other studies. Our model also distinguishes New Zealand and Australia as separate regions, allowing us to present regionally specific results not available from most models. Secondly, we consider a scenario in which a relatively broad coalition of China plus all OECD countries implement carbon taxes that are harmonised internationally and rise over time.[2] We estimate not only the average (i.e. overall) leakage rate for this scenario, but also the marginal effects with respect to participation in the coalition of each one of its member regions. These marginal effects not only provide insight into the sources of leakage, but could be more directly interpreted in the context of a region's incentives to join (or to defect from) such a coalition. The breadth of the coalition considered together with the country/region-specific results presented distinguishes our study from previous contributions. While a harmonised carbon tax appears much less likely to eventuate than expansion (and possibly international linkages) of cap-and-trade schemes, the scenario

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[1] This is not to deny widespread acceptance of countries' differing levels of responsibility and capability to undertake mitigation actions. For example, it is agreed in the Copenhagen Accord that in relation to mitigation actions, 'Least Developed Countries and Small Island Developing States may undertake actions voluntarily and on the basis of support' (UNFCCC Decision 2/CP.15, Art. 5).

[2] By focussing on the role of China, we do not mean to ignore the importance of actions already taken or promised by many developing countries; particularly, under the Copenhagen Accord. We have focussed only on China here because of its size, growth rate and its focus on energy and industrial emissions. The focus of some other countries is rightly in other areas. For example, Brazil's top priority is to reduce emissions from deforestation.

allows us to focus on the effects of the carbon price, abstracting from cap-dependent feedbacks that would affect marginal leakage rates.

Literature review

The rate of carbon leakage l_n due to price- or quantity-based regulation of emissions in one or more countries is usually defined as the resulting increase in emissions in non-participating countries (ΔE_s) divided by the reduction in emissions (ΔE_n) achieved by the participating countries (Felder and Rutherford, 1993):

$$l_n = \frac{\Delta E_s}{\Delta E_n} \tag{0.1}$$

Carbon leakage can also occur within or between sectors if emissions of some firms or some sectors are not covered (directly or indirectly) by the regulation.

The literature on leakage identifies different channels through which it can arise (Böhringer and Löschel, 2002; Di Maria and van der Werf, 2008; Felder and Rutherford, 1993), related to the effects of climate policies on relative prices of both goods and factors (Di Maria and van der Werf, 2008). The most direct driver of emissions leakage is changes in costs and thence relative international competitiveness of firms in EITE industries. Increased costs due to carbon pricing may result in the relocation of production to countries with no (or lower) carbon prices. Leakage also occurs because decreased demand for fossil fuels in emissions-pricing countries lowers the price of fossil fuels globally. Lower fossil fuel prices induce producers (and consumers) in those countries to substitute towards fossil fuels. Leakage can also occur as a result of income and terms of trade effects that are caused by carbon pricing. Leakage via these latter channels, and in some circumstances, even the fossil fuel price channel, may be negative rather than positive.

Felder and Rutherford (1993) analyse leakage using a recursively dynamic general equilibrium model with six regions and international trade of energy and non-energy goods for the period from 1990 to 2100. They find evidence of significant leakage through both trade and price-induced substitution channels. This is confirmed in Böhringer and Löschel (2002), while Burniaux and Oliveira Martins (2012) conclude that leakage through trade has less of an effect due to the insensitivity of their results to the values of Armington elasticities. Other CGE analyses also find that the price-induced substitution channel is the quantitatively more important in the short- to medium-term (Di Maria and van der Werf, 2008; Kuik, 2005; Zhou et al., 2010).

A number of authors use partial equilibrium models of energy intensive industries to estimate sector specific leakage rates for iron and steel (Gielen and Moriguchi, 2002; Monjon and Quirion, 2010; Reinaud, 2005), cement (Demailly and Quirion, 2006; Monjon and Quirion, 2010; Ponssard and Walker, 2008; Reinaud, 2005), newsprint (Reinaud, 2008), aluminium (Monjon and Quirion, 2010; Reinaud, 2005) and electricity (Monjon and Quirion, 2010). Many of these studies find high leakage rates for specific sectors. While it is likely that some narrowly defined industries are indeed exposed to high rates of leakage, the inherent upward bias of such partial equilibrium results must also be considered (Karp, 2011). In a general equilibrium setting, factor prices can adjust downward, partially offsetting increased production costs due to a carbon tax in the carbon-intensive sectors (Karp, 2012).

On the other hand, it is argued that the high level of sectoral aggregation of most general equilibrium models creates a downward bias (Reinaud, 2008). Caron (2012) studies the effects of different levels of aggregation and concludes that even very high levels of aggregation cause only a modest downward bias of aggregate leakage rates when compared to a model in which industrial production is highly disaggregated. Aggregation does result in lower estimates of leakage at the sector level and can create more significant biases in estimates of the efficiency of measures such as border carbon taxes.

Burniaux and Oliveira Martins (2012), Zhou et al. (2010) and Karp (2012) provide reviews of CGE model estimates of leakage. Estimates of leakage rates vary widely depending on the type of model used (static, recursive dynamic or intertemporal), parameter estimates, and policy assumptions. Estimates typically range from estimates of 2–10% (Burniaux, 2001; Burniaux and Oliveira Martins, 2000; Mattoo et al., 2009; McKibbin et al., 1999; McKibbin and Wilcoxen, 2008; OECD, 2009; Oliveira Martins et al., 1992; Paltsev, 2001) to estimates of 20-30% (Böhringer et al., 2012; Böhringer and Löschel, 2002; Bollen et al., 1999; Energy Modeling Forum, 2000; Light et al., 1999). Brown et al. (1997), using the recursive dynamic GE model MEGABARE, estimate leakage rates between those above; 12-14% depending on the stringency of emissions reductions in Kyoto Annex I countries. While the general consensus of CGE modelling studies of a variety of climate policies is that leakage rates are low or moderate, there are outlying studies that find high leakage rates. Notably, Babiker (2005) finds that with imperfect competition and capital mobility, leakage rates could exceed 100%.

While there are many estimates of global leakage rates, fewer studies consider how different sectors or regions contribute to overall leakage rates. Paltsev (2001) employs a sophisticated decomposition method to identify bilateral contributions to leakage that results from implementation of the Kyoto Protocol. The European Union, the United States and Japan are the sources accounting for 41%, 29% and 17% of leakage respectively, while China and the Middle East the main destinations of leakage. The chemical, and iron and steel industries are the main source sectors for leakage, accounting for 20% to 17% of global leakage, respectively.

Zhou et al. (2010) and Burniaux and Oliveira Martins (2012) also review drivers of the variation in estimated leakage in computational models. Several key factors influence the magnitude of leakage:

- *Size of the country coalition*. Small increases in the size of the coalition leading to substantial reductions in leakage (Böhringer et al., 2012).
- *Energy supply elasticities.* Burniaux and Oliveira Martins (2012) find that the magnitude of leakage was largest when there was inelastic supply of coal, with the elasticity of supply of oil having less of an influence on the estimated magnitude of leakage (Burniaux and Oliveira Martins, 2000). Oliveira Martins (1995) find the possibility of negative leakage due to a fall in the relative price of oil versus coal inducing a shift towards less carbon-intensive energy sources, such as oil, in non-participating countries.
- *Substitution possibilities in production.* Burniaux and Oliveira Martins (2000) assess the sensitivity of carbon leakage to changes in key elasticities, and concluded that the rate of leakage is higher, the higher the inter-fuel elasticity of substitution. For example, Böhringer and Löschel (2002) find the magnitude of leakage was very sensitive to the representation of fossil fuel markets, with higher leakage estimated for cases of higher assumed substitutability between crude oil and coal from different regions.

- *International mobility of goods and capital*. The more internationally mobile is capital and the higher are trade substitution elasticities (Armington elasticities), the more leakage is likely to occur via the competitiveness channel (Burniaux and Oliveira Martins, 2012; Zhou et al., 2010). McKibbin et al. (1999) find that most capital reallocation under the Kyoto Protocol would be to Annex I countries, rather than to non-Annex I countries. This meant that the contribution of capital mobility to carbon leakage was small. Further, the magnitude of leakage via capital mobility is ultimately influenced by the trade substitution elasticities (Burniaux and Oliveira Martins, 2000).
- *Technical change.* Technical change may be induced when relative prices of carbon-intensive goods affect the relative profitability of technologies for goods that are less carbon-intensive. While considered in few of the studies cited above, endogenous technical change always reduces carbon leakage and may reverse it with sufficiently high elasticities of demand for carbon-based energy (Di Maria and van der Werf, 2008).

Overall, estimates of leakage tend to be small or moderate, with large leakage rates only occurring in cases where implausible values of supply, trade substitution and inter-fuel substitution elasticities are used (Burniaux and Oliveira Martins, 2012).

Average and marginal leakage rates

We define the average leakage rate due to pricing a subset P of global emissions as:

$$l_P \equiv \frac{\sum_{j,s\notin P}\Delta E_{j,s}}{\sum_{i,r\in P}\Delta E_{i,r}}\cdot 100\% \tag{0.2}$$

where i or j denote different categories of emissions and r or s denote different regions. The change in emissions of category i in region r with respect to the baseline scenario is given by $\Delta E_{j,s}$. Here, the set P includes industrial and energy emissions in those regions that price these emissions.

We also define a marginal leakage rate, not in relation to a marginal change in price – as in Felder and Rutherford (1993) – but in relation to the regional scope of participation. These rates are defined as:

$$\tilde{l}_q \equiv \frac{\sum_{j,s\notin P}\Delta\tilde{E}^q_{j,s} + \sum_{\{i,r|r\in P \text{ and } r\neq q\}}\Delta\tilde{E}^q_{i,r}}{\sum_{\{i,r|r\in P \text{ and } r=q\}}\Delta\tilde{E}^q_{i,r}}\cdot 100\% \tag{0.3}$$

We compare the change in global emissions in regions other than q when region q participates along with other coalition regions, compared to the case where region q fails to participate. We use the tilde and superscript q to indicate this marginal change in emissions.

As the numerator in the leakage equations involves summation over categories of emissions and over regions, we can decompose overall average or marginal leakage rates into additive contributions of different industrial sectors and the household sector in different regions. We can also decompose leakage to show the contributions of changes in output (or for households, consumption expenditure) and changes in emissions intensity of production (or consumption).

Leakage caused by relocation of production and income effects will be seen in changes in output. Changes in emissions intensities reflect price-induced substitutions.[3]

To decompose leakage into contributions from changes in output and emissions intensity in production, we define the emissions intensity of output as emissions divided by output. The change in emissions is then equal to the change in the product of emissions intensity and output. That product can be decomposed additively into (i) a contribution due to the change in output given constant emissions intensity, $\varepsilon_k \Delta Y_k$, (ii) the change in emissions intensity given constant output, $\Delta\varepsilon_k Y_k$ and (iii) an interaction term, $\Delta\varepsilon_k \Delta Y_k$. If the percentage changes in emissions intensity and output are both small, the interaction term will be negligibly small.

$$\begin{aligned} l_P &= \frac{\sum_{j,s\notin P} \Delta\left(\varepsilon_{j,s} Y_{j,s}\right)}{-\sum_{i,r\in P} \Delta E_{i,r}} \\ &= \frac{\sum_{j,s\notin P} \varepsilon_{j,s} \Delta Y_{j,s} + \sum_{j,s\notin P} \Delta\varepsilon_{j,s} Y_{j,s} + \sum_{j,s\notin P} \Delta\varepsilon_{j,s} \Delta Y_{j,s}}{-\Delta E_k} \cdot 100\% \end{aligned} \tag{0.4}$$

While the earlier literature on carbon leakage tended to focus on the effects of emissions taxes, the most recent literature has tended to focus on emissions trading schemes (ETS) in which the aggregate emissions are capped at sectoral, national or even multinational levels. Evidently, if regional emissions are capped, this directly determines the denominator in the leakage rate equation. However, in the case of a tax, as analysed here, the terms in both the numerator and denominator are determined endogenously. This difference is most important when it comes to our estimates of marginal emissions leakage rates. In this case, whether or not region *q* prices its emissions affects not only the aggregate emissions of unregulated regions *s*, but also of other regulated regions, *r*.

With regional emissions caps, the actions of any one region can cause changes in the aggregate emissions of only regions without emissions caps. With harmonised carbon taxes though, the actions of any one region can cause changes in the aggregate emissions of *all* other regions. However, other things being equal, the higher the carbon price of a region, the less leakage should occur in that region. This is because a carbon price introduces a wedge between the producer price of a fossil fuel and its user cost. If we assume that substitution between this fossil fuel and non-fuel inputs in production (or consumption) is isoelastic, a given decrease in the producer price of the fossil fuel due to decreased global demand (price-induced substitution channel) has relatively less effect on the user cost, the higher the carbon tax. This is illustrated for a hypothetical case involving a Cobb-Douglas production function in Figure 1.

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[3] A decomposition of leakage rates that isolates contributions of terms within both the numerator and the denominator is given in Paltsev (2001) This involves integrating numerically the effects of marginal changes in any one region's emission constraint.

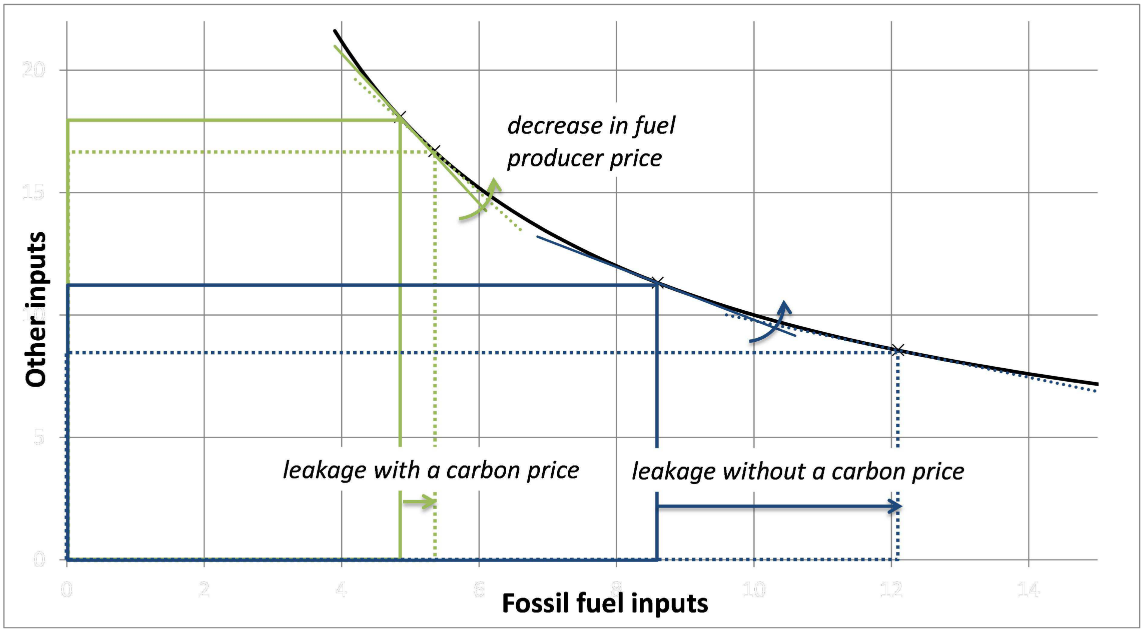

Figure 1 – The effects of a carbon price wedge on emissions leakage via the price substitution channel. More leakage occurs without a carbon price than with a carbon price.

Model

The model CliMAT-DGE (Climate Mitigation, Adaptation and Trade in Dynamic General Equilibrium) is a multiregional intertemporal general equilibrium model (Lennox et al., 2011).[4] Following Mathiesen (1985) and Lau et al. (2002), the model is formulated as a mixed complementarity problem (MCP) in GAMS™ and solved using the PATH solver (Ferris and Munson, 1998) with a five-year time-step with a horizon of 125 years. It is calibrated to the GTAP 7 database, which has a base year of 2004.[5]

The number and definitions of regions in the model can be changed, depending on the question at hand and on computational limitations on overall model size. Here, we define eight regions:

- New Zealand – NZL
- Australia – AUS
- North America (United States and Canada) – NAM
- Europe (European Union and rest of Europe) – EUR
- Other of the OECD countries – OEC
- China – CHN
- Non-OECD oil-exporters[6] – OIE
- Other non-OECD – NOE

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[4] CliMAT-DGE was developed by the authors as the central component of the New Zealand Integrated Assessment Modelling System (NZIAMS), which consists of tightly linked economic, climate and impact modules.

[5] At the time of writing, we are in the process of updating to the GTAP 8 database, which has a base year of 2007.

[6] We include all OPEC countries plus Azerbaijan, Kazakhstan, plus three GTAP 'rest of …' regions (Rest of Central Africa, Rest of South-East Asia, Rest of Former Soviet Union) that have substantial oil and/or gas production.

In each region, we model a single representative household. There is no government sector. We assume that each representative household has perfect foresight and maximises the discounted sum of its instantaneous utilities, subject to a lifetime income constraint. We assume a 5% private discount rate. Income is derived from the households' endowments of labour and other factors of production (see below). Instantaneous utilities are modelled using a nested constant elasticity of substitution (CES) and Cobb-Douglas structure.

In each region, goods are produced by firms that are assumed to be identical within each production sector and to operate with constant returns to scale in perfectly competitive markets. The definition of energy sectors in CliMAT-DGE is fixed, while the number and definition of non-energy sectors can be varied (again, depending on the question at hand and computational limitations on overall model size). The energy sectors are:

- Coal extraction – COA
- Oil extraction – OIL
- Gas extraction and supply – GAS
- Petroleum refining – P_C
- Fossil electricity generation – EFS
- Carbon-free electricity generation – ECF

For this study, we define five non-energy sectors:

- Agriculture – AGR
- Forestry – FST
- Food processing – FOO
- Energy-intensive manufacturing and transport – EMT
- Non-energy-intensive manufacturing and services – NSV

Firms' technologies are described by nested constant elasticity of substitution (CES), Cobb-Douglas and Leontief production functions. Different nesting structures are used for agriculture and forestry sectors, each of the energy sectors, and for manufacturing and service sectors. These functions and the elasticities of substitution are largely based on the MIT EPPA model (Babiker et al., 2008; Paltsev et al., 2005). There is a one-to-one mapping between sectors and goods, with the exception of electricity, which is produced by both the fossil and carbon-free electricity sectors.

All sectors use energy and other intermediate inputs, labour and capital. The agriculture and forestry sectors use land, which is allocated between them with a constant elasticity of transformation (CET) function. The coal, oil, gas and carbon-free electricity sectors use sector-specific resources of which households have a fixed endowment in each period. In the case of primary energy sectors, these provide an *ad hoc* way to account for increasing costs of production associated with resource depletion, while abstracting from the complexities of heterogeneous and uncertain reserves. In the case of the carbon-free electricity sector, the sector-specific resource provides an *ad hoc* way to account for the various natural and social constraints on expansion of hydroelectric, nuclear, solar, wind and most other renewables.

In CliMAT-DGE, installed capital can be modelled as mobile or immobile between sectors. Here, we are particularly interested in the process of economic adjustment as a carbon price is introduced and increased over time, so we model installed capital as sector-specific. For sector i in region r at time t, capital stocks $K_{i,r,t}$ depreciate at a constant rate δ and are increased through new investment. We distinguish between gross investment $I_{i,r,t}$ and net investment $J_{i,r,t}$, assuming quadratic adjustment costs following the specification of Uzawa (1969):

$$K_{i,r,t+1} = (1-\delta) K_{i,r,t} + J_{i,r,t} \tag{0.5}$$

$$I_{i,r,t} = J_{i,r,t} \left(1 + \frac{\phi}{2} \frac{J_{i,r,t}}{K_{i,r,t}} \right) \tag{0.6}$$

The adjustment cost parameter ϕ is set to 0.2. Assuming a 5% depreciation rate, this gives adjustment costs of approximately 4% for a 2% growth rate, or 6% for a 5% growth rate.

Regions are linked by bilateral trade flows. Following the Armington (1969) assumption, we model imperfect substitution firstly, between domestic goods and imports and secondly, between imports from different regions using a nested CES structure. Bilateral trade flows are associated with demands (in fixed proportions) for international transport services.

We model household- and industry-specific indirect taxes and subsidies on intermediate and final consumption of goods, use of capital, labour, land and sector-specific factors, imports and exports. As household labour supply is fixed in each period, taxes are returned to the representative household as a lump sum. Households also derive income from their endowments of land and sector-specific resources. Finally, households derive income from the initial value less the terminal value of their sector-specific capital stocks – the latter being determined by the model's terminal conditions (Lau et al., 2002).

Baseline

As CliMAT-DGE is a dynamic model, the benchmark data and elasticities do not completely specify the model. It is also necessary to specify endowments of labour, land and sector-specific factors as well as the paths of any time-varying parameters. The simplest way to do this is to assume the economy follows a balanced growth path. However, in a long-term, global context, this is highly unrealistic. We therefore calibrate the model to follow a baseline defined by long-term population and macroeconomic projections.

We take as our starting point the projections to 2050 for 128 countries developed by Fouré et al. (2010). We extrapolate these projections to the remaining countries and regions in the GTAP database and beyond 2050. In the period to 2050, the rapid growth of countries such as China and India is projected to decelerate, but only slowly. For computational reasons, we require that global growth is approximately balanced towards the end of the model horizon of 125 years. We therefore impose in our extrapolations an accelerating rate of convergence to a common growth rate. This satisfies the technical requirement for terminal balanced growth while minimally affecting the first half of the simulation horizon, with which we are mainly concerned.

In the version of the baseline used in this paper, we allow only for general increases in labour productivity. We have also made the simplest possible assumptions in relation to the calibration of sector-specific factors for primary energy supply and carbon-free electricity. Specifically, baseline shares of fossil versus non-fossil electricity generation are maintained as are baseline ratios of coal, oil and gas outputs relative to GDP. Consequently, emissions increase more in our baseline scenario than is realistic, especially in the case of many developing countries with higher rates of technological progress. In a future version of the baseline, we plan to account for autonomous energy efficiency improvements (AEEI) and analogous technological changes that reduce industrial and agricultural GHG intensities of production. We also plan to account for projections of fossil fuel and carbon-free electricity supply.

Carbon taxes

We model the introduction of an internationally harmonised tax on energy and industrial GHG emissions in the five developed country regions (NZL, AUS, NAM, EUR, OEC) and China (CHN). These countries account for approximately two thirds of global emissions (excluding emissions from land use change) in the baseline. This tax is set at US$$_{2004}$ 15/tCO_2eq in the first period (2013-2017) and rises at a real rate of 5% per annum thereafter. Our analysis focuses on the adjustment to such a carbon price trajectory, not on its very long run effects. We present and discuss results only for the first six periods that cover the years 2013 to 2042. Consequently, in the version of the model used for this paper, we do not include backstop technologies (e.g. electricity generation with carbon capture and storage) and we cap the carbon price at US$100/t from the period ending 2057, holding it constant through the remainder of the simulation (i.e. until 2137).

The carbon pricing scenario modelled here is designed for simplicity rather than realism. Directly equalising the marginal abatement cost between regions ensures intra-temporal efficiency. The carbon price trajectory ensures a reasonably intertemporally efficient solution. With regional cap and trade schemes, international emissions trading and emissions banking and borrowing are needed to achieve intra- and intertemporal efficiency respectively. Similarly, we assume that all countries participate (or not) in a carbon pricing coalition on exactly the same basis, either adopting the common carbon price from the start, or opting out entirely.

To calculate marginal leakage rates, we conduct additional simulations, leaving one of the coalition regions out of the coalition at a time. Marginal leakage rates are then be calculated by comparing emissions under each of these scenarios with emissions in the scenario with participation of all five developed country regions and China.

Results

Emissions reductions and macroeconomic impacts of carbon taxes

For the carbon pricing scenario, changes in GDP relative to the baseline scenario are shown in Table 1, up to 2042. These impacts increase over time in all regions; as expected, given the rising carbon price path. The largest reductions of GDP are for China, followed by the oil exporters (OIE) region. Of the developed regions, the largest reductions of GDP are for Australia. In fact, GDP initially increases slightly in the other developed regions, only falling below the baseline after the second period. Impacts on the Rest of Non-OECD (NOE) region GDP are small and are also positive for the first two periods. The initial positive effects are due to the forward-looking behaviour in the model. Carbon pricing lowers the optimal level of capital stocks, resulting in reduced investment and increased consumption at the start of the transition.

Table 1 – Change in GDP relative to the baseline with carbon pricing in NZL, AUS, NAM, EUR, ROE and CHN

	$/tCO$_2$-eq	NZL	AUS	NAM	EUR	ROE	CHN	OIE	NOE
2017	$ 15.00	0.45%	-0.96%	0.43%	0.27%	0.34%	-7.88%	-4.59%	0.23%
2022	$ 19.14	0.12%	-1.24%	0.18%	0.00%	0.02%	-8.70%	-4.89%	0.04%
2027	$ 24.43	-0.17%	-1.51%	-0.04%	-0.24%	-0.24%	-9.79%	-5.33%	-0.04%
2032	$ 31.18	-0.45%	-1.79%	-0.29%	-0.49%	-0.50%	-10.99%	-5.81%	-0.08%
2037	$ 39.80	-0.74%	-2.10%	-0.58%	-0.78%	-0.78%	-12.35%	-6.43%	-0.12%
2042	$ 50.80	-1.07%	-2.47%	-0.96%	-1.14%	-1.12%	-13.84%	-7.16%	-0.19%

Relative to the baseline emissions, carbon pricing reduces global emissions in CO_2-equivalent units[7] by 9% in the first period and by approximately 3% more in each subsequent period (Table 2). Note that while agricultural emissions are not subject to carbon pricing, they are accounted for in these figures. Of the carbon-pricing regions, China achieves the largest relative emissions reductions while New Zealand achieves the least. Emissions increase very slightly in the OIE region and more significantly in the NOE region.

Table 2 – Change in CO_2-eq emissions relative to the baseline with carbon pricing in NZL, AUS, NAM, EUR, ROE and CHN

	$/tCO$_2$-eq	NZL	AUS	NAM	EUR	ROE	CHN	OIE	NOE	Global
2017	$ 15.00	-5%	-15%	-13%	-9%	-9%	-27%	1%	4%	-9%
2022	$ 19.14	-10%	-20%	-19%	-15%	-13%	-37%	1%	4%	-14%
2027	$ 24.43	-13%	-23%	-23%	-19%	-15%	-44%	1%	4%	-18%
2032	$ 31.18	-16%	-26%	-27%	-23%	-18%	-50%	2%	5%	-22%
2037	$ 39.80	-18%	-29%	-31%	-26%	-21%	-55%	2%	5%	-25%
2042	$ 50.80	-21%	-32%	-35%	-30%	-24%	-60%	3%	6%	-29%

The main features of the results presented in Table 1 and Table 2 can be explained firstly in terms of overall emissions intensities of GDP in carbon-pricing regions, secondly as a result of reduced global demand for fossil fuels, which is the main factor affecting the OIE region and thirdly, as a result of differences in the sectoral structures of each region. As concerns structural differences, our analysis of the results focusses on two of the most important ratios. These are the baseline ratio of agricultural to energy and industrial greenhouse gases and the baseline ratio of carbon-free to fossil electricity generation[8].

China is most obviously affected by a high baseline emissions-intensity of GDP, due to the importance of emissions-intensive industries in its economy as well as the relatively high emissions intensities of many producers in these industries compared to producers in other countries. However, major caveats here are that our current model database is dated (i.e the 2004 GTAP database) and that we have not accounted for improvements in sectoral energy- or emissions-intensities in our baseline. Consequently, our baseline exaggerates both emissions growth and mitigation potential for China in absolute terms and relative to the developed country regions.

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[7] All figures reported for emissions exclude any changes relating to land use change and forestry, which we have not modelled.

[8] We use this term loosely to cover nuclear power, hydroelectricity, and renewables that include solar, wind and biomass.

While there are many differences in baseline economic structure and industry emissions-intensities of the developed country regions, the relative importance of agricultural emissions for a region and/or its (remaining) scope to switch from fossil to carbon-free electricity generation go a long way to explaining the observed differences in macroeconomic impacts and aggregate emissions reductions. For example, Australia has a high reliance on coal-fired electricity in the baseline (left panel of Figure 2) and achieves large emissions reductions by increasing its carbon-free generation capacity and reducing its fossil generation capacity (left and right panels respectively in Figure 3). China presents a more extreme case of this pattern, given the lower efficiency of its power plants.[9] In the case of New Zealand, the baseline share of carbon-free generation is already high[10] in its generation mix, so the electricity sector presents more limited mitigation opportunities. The unusually high share of agricultural GHGs in New Zealand's baseline emissions profile is also very important (right panel of Figure 2. In our scenario, there is no direct incentive to reduce these emissions.

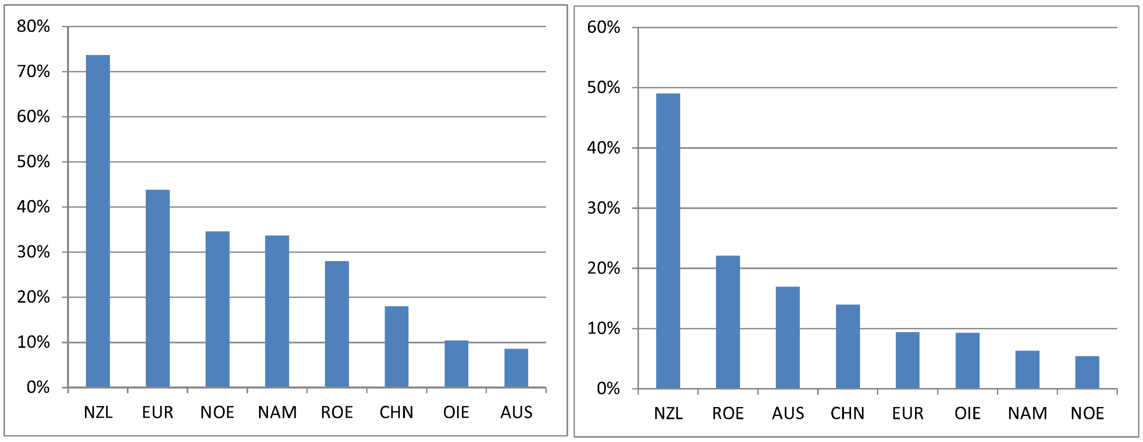

Figure 2 - Baseline shares (in the first period) of carbon-free electricity generation (left) and agricultural GHGs (right)[11]

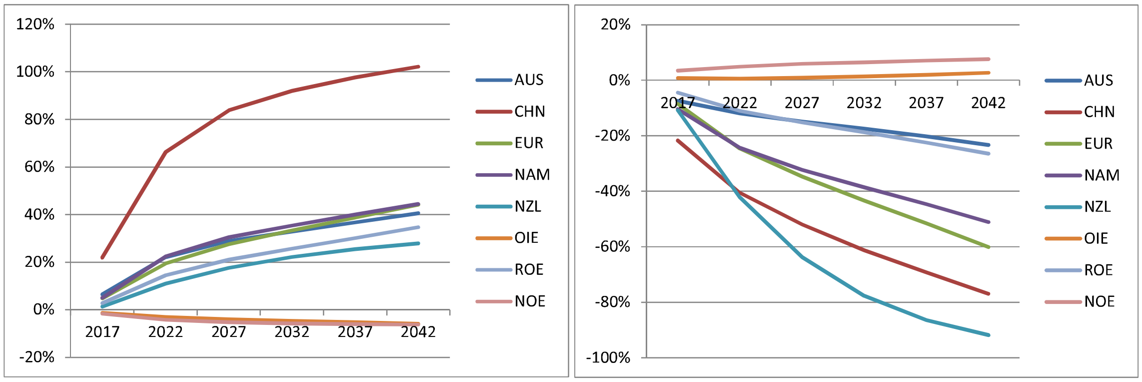

Figure 3 – Percentage changes in output of carbon-free (left) and fossil (right) electricity generation

In Figure 3, it can also be seen that in the carbon-pricing scenario, carbon-free electricity generation decreases and electricity fossil generation increases slightly relative to the baseline in the OIE and NOE regions. This is due to the decrease in fossil fuel prices.

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[9] Here again, it is important to note that we have not allowed for improvements in the efficiency of new Chinese power plants in our current baseline.

[10] Predominantly hydroelectricity, but also wind turbines and other types of renewable generation.

[11] Note that these shares are not constant over time in the baseline, but changes are relatively small.

Average and marginal emissions leakage rates

With harmonised carbon prices but partial sectoral and regional coverage, leakage can occur both within and outside the carbon-pricing coalition countries. In Figure 4, which shows leakage rates over time for our carbon-pricing scenario, we refer to changes in agricultural CH_4 and N_2O emissions (which are accounted for but not priced[12]) in the coalition regions as 'domestic leakage' (dom). We refer to (any) changes in emissions of the non-coalition OIE and NOE regions as 'external leakage'. We decompose external leakage into contributions from changes in output (dY) and changes in emissions intensity (de). All three of these contributions decline over time, but the most obvious feature is the sharp decline in the contribution of the emissions-intensity channel in the first decade. The contribution of domestic leakage is actually negative. This is likely to be due to the dominance of negative income effects on agriculture in the coalition regions.

Our total leakage rates are at the bottom end of the range found in general equilibrium studies. This is to be expected, given that we model a relatively broad application of a harmonised carbon price. Equalising marginal abatement costs between regions significantly reduces global leakage rates (Paltsev, 2001), while including China in our carbon-pricing coalition removes a major destination for leakage: China accounts for 3.2% out of a total 10.5% in Paltsev's study of the Kyoto Protocol (*Ibid.)*. We find that the contributions of output and emissions intensity to international leakage are roughly equal in the medium and long term. As discussed below, fuel price changes may account not only for increases in emissions intensity, but under some conditions, also increases in output. Thus, these results suggest that changes in fossil fuel prices are as or more important than other channels of leakage, which is in agreement with much of the literature.

We find a higher short-term rate of leakage due to changes in emissions intensity, which can be explained by the immobility of installed capital. As concerns the EITE industries, this dampens both output decreases in the coalition regions and output increases in the non-coalition regions. This has an ambiguous effect on the rate of leakage. However, effects on the fossil fuel supply are clear-cut. The immobility of capital makes the supply of fossil fuels less elastic in the short term than the long term. Consequently, the fuel price-induced leakage channel is stronger in the short term. The importance of this effect in our model is contingent on the constancy of elasticities of substitution. If elasticities of substitution between fossil fuels and other inputs are lower in the short-term than in the long term, as is likely, this effect will be weakened and might even be reversed.

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[12] In addition, there may be emissions or removals from land use change and in soil carbon, but we have not modelled these sources and sinks here.

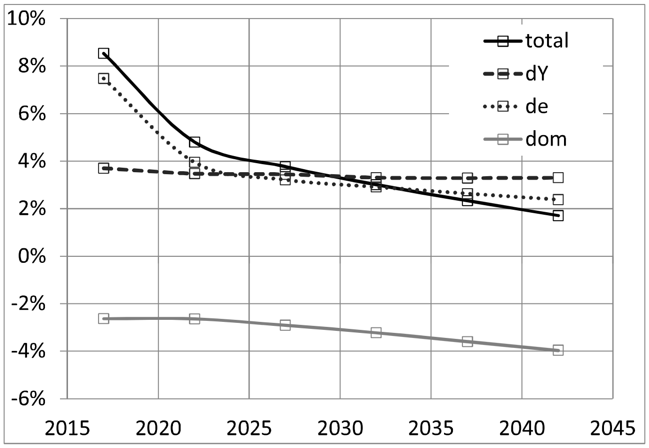

Figure 4 – Rates of emissions leakage with uniform carbon pricing in the five OECD countries/regions and China

In figures 5 – 10, we present marginal leakage rates with respect to the participation of each of the six regions. As explained above, we define marginal leakage rates with respect to participation of a region *j* in the carbon pricing coalition as the change in emissions of all other regions and the change in own agricultural emissions divided by the change in own energy and industrial emissions when *j* participates, compared to the case where *j* does not participate. The marginal rate leakage is broken down to distinguish leakage to regions participating in the carbon pricing coalition (co), regions not participating in the coalition (nco) and domestic leakage (dom). Unlike a regional cap-and-trade scheme, leakage can occur in regulated sectors of the remaining coalition regions, since the exogenous carbon price fixes their marginal abatement costs rather than their total industrial and energy emissions.

The co and nco total leakage are further broken down to distinguish contributions of changes in output (dY) and changes in emissions intensity (de).[13] This helps to identify the different channels of leakage. Changes in emissions intensity will mainly reflect fossil fuel price-induced substitutions. Income and carbon-price cost effects will mainly cause changes in output. However, changes in fossil fuel prices also affect production costs and so may also contribute to output changes.

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[13] While we have not presented the detailed results here, almost all domestic leakage is due to changes in agricultural output rather than agricultural emissions intensity.

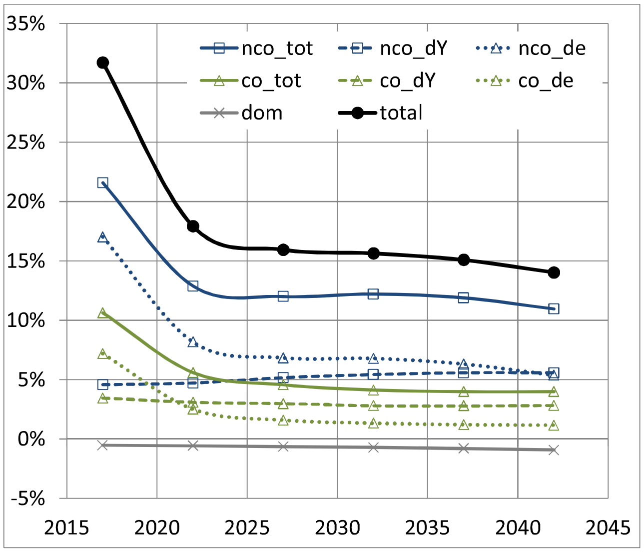

Figure 5 – Marginal leakage rates and channels for Australia (AUS)

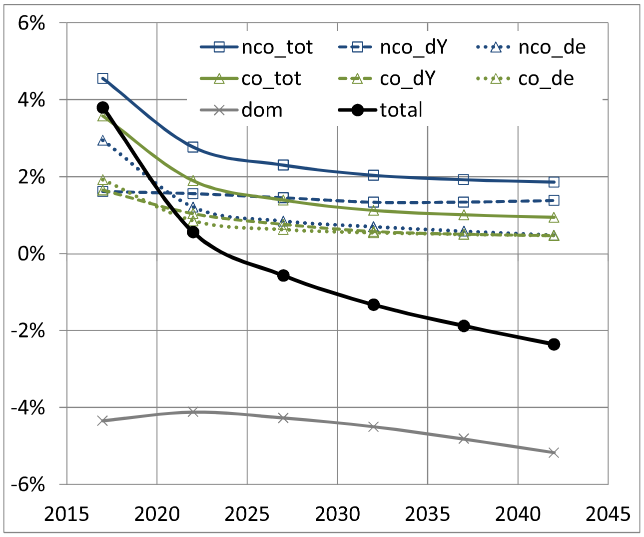

Figure 6 – Marginal leakage rates and channels for China (CHN)

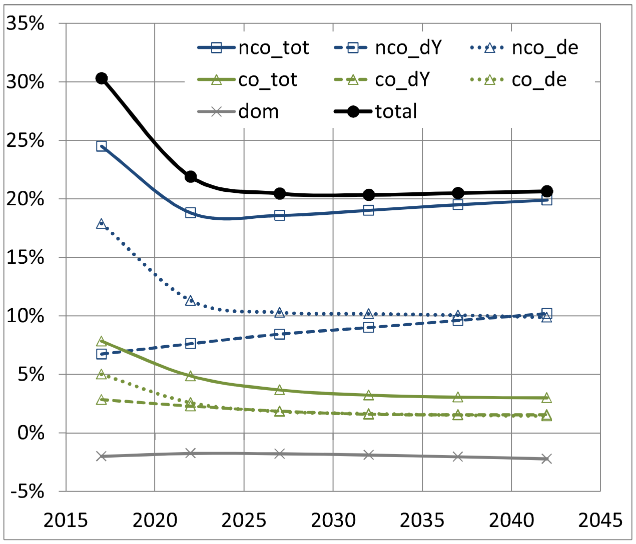

Figure 7 – Marginal leakage rates and channels for the Europe (EUR)

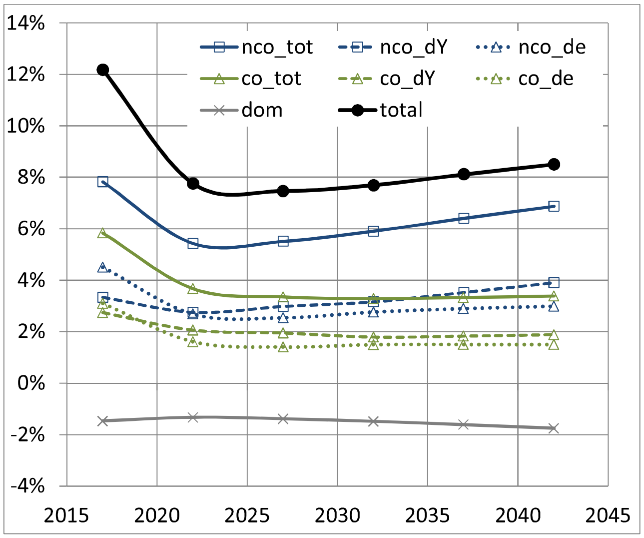

Figure 8 – Marginal leakage rates and channels for US/Canada (NAM)

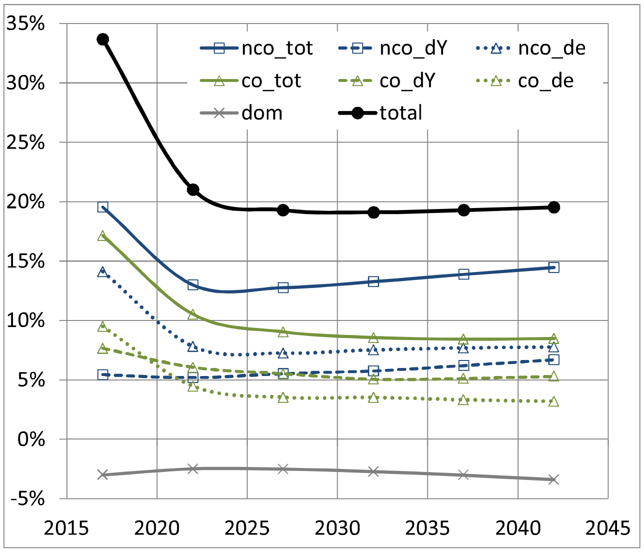

Figure 9 – Marginal leakage rates and channels for New Zealand (NZL)

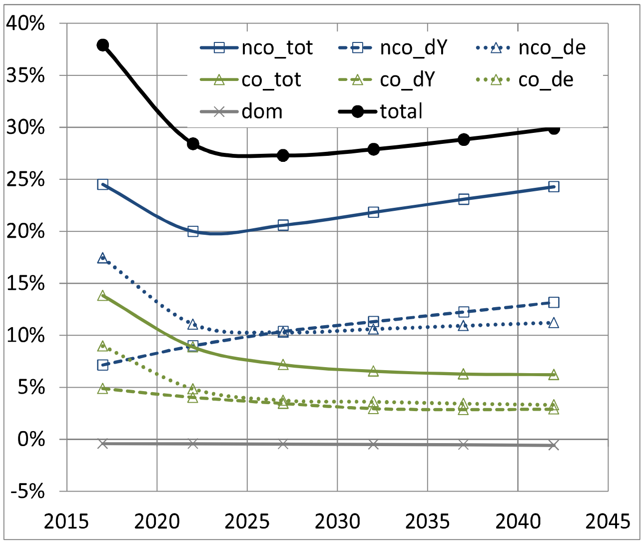

Figure 10 – Marginal leakage rates and channels for Rest of OECD (ROE)

Figures 5 – 10 show that marginal leakage rates with respect to participation are, with the notable exception of China, much higher than the average leakage rates. Marginal leakage rates are highest for the Rest of OECD region (which includes Japan), followed closely by New Zealand and Europe. Rates for Australia are somewhat lower and for North America, much lower again. As for the average leakage rates, the contribution of changes in emissions intensity are higher in the first period than subsequent periods. Thereafter, rates are more stable, but for China there is a strong downward trend, while for North America and the Rest of OECD there is a modest upward trends.

Leakage rates depend on the carbon price, the fraction of global emissions to which the price is applied, differences in emissions intensity of production and other differences in economic structure. Thus, low and declining marginal leakage rates for China reflect its very large and rapidly growing economy, as well as its relatively high share of EITE industries and high emissions-intensities of production within those industries. At the other extreme, high and rising marginal leakage rates for the Rest of OECD region can be explained – despite its relatively large size – by very low emissions intensities of production and low growth rates. These differences should be treated with some caution, given the limitations of the baseline we have used for this study. Had we accounted for relatively rapid improvements in Chinese energy efficiency in our baseline, the long-run downward trend for China would be weaker, or might even be reversed.[14]

The decomposition of marginal leakage rates provides further insight into the causes of leakage in different regions and at different times. We see that leakage to non-coalition regions exceeds leakage to coalition regions in all cases (by a factor of approximately two in most cases). This is due to the larger share of coalition regions in the global economy, the lower emissions intensities of coalition regions compared to non-coalition regions (except in the case of China), and the effect of the carbon price in coalition regions on leakage through the emissions intensity channel, as was illustrated conceptually in Figure 1. For the EU and for China, long-run marginal leakage rates associated with increased emissions intensity within coalition regions is comparable to that associated with increased output within coalition regions. However, for the other four coalition regions, the former rates are significantly smaller than the latter.

Marginal domestic leakage rates (i.e. changes in agricultural CH_4 and N_2O emissions) are negative for all regions. This implies that income and external demand effects, combined with direct and indirect effects on agricultural costs of pricing CO_2 emissions dominate any offsetting substitution or terms of trade effects. Particularly large negative rates for China correspond to the large negative income effects (Table 1). New Zealand has the second largest (negative) marginal domestic leakage rate. This is due to the relatively large size of New Zealand's export-oriented agricultural sector, rather than to direct income effects, which are the second smallest of all coalition regions.

If we consider contributions to the average leakage rates by sector in which leakage occurs (Figure 11), we see that the largest positive contributions to the average leakage rates are from fossil electricity generation (EFS), followed by energy-intensive manufacturing and transport (EMT), with final consumption (CON) the third most important contributor. Comparing these contributions between the periods ending 2017 and 2042, we see the dominant contribution of

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[14] From 1994 to 2003 China's aggregate energy intensity of GDP declined 69.4 grams of standard coal equivalent (GSCE) per RMB Yuan (constant prices), with reductions due to technological change offsetting increased energy intensity associated with structural changes in the economy (Ma and Stern, 2008).

increased emissions intensities in the short run, especially in the case of EFS. Interestingly, the rate of leakage due to increases in output of the EFS sector decreases slightly over time, while it increases slightly for the EMT sector. Substitution effects are dominant in the case of final consumption and in fact, consumption is slightly reduced due to negative income effects in the non-coalition regions.

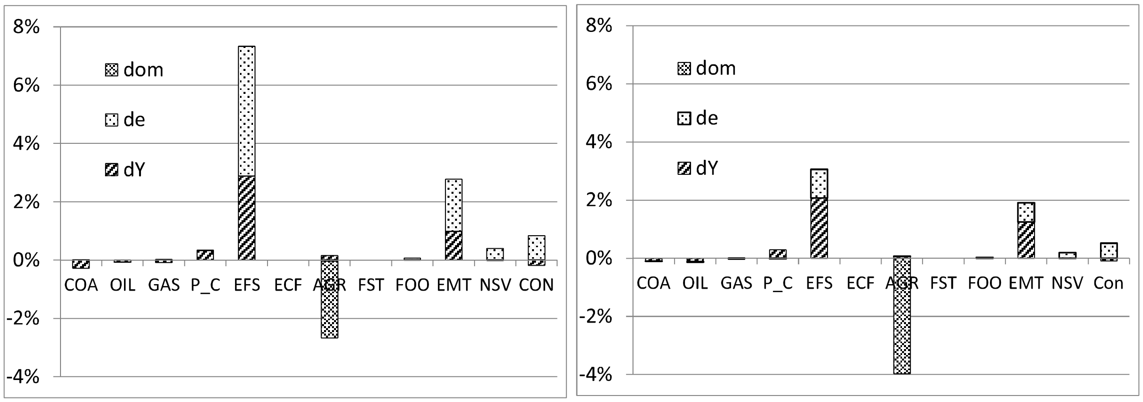

Figure 11 – Decomposition of average leakage rates in 2017 (left) and 2042 (right) by sector of leakage and by changes in international output, international emissions intensity and domestic (agricultural) emissions.

The important contribution of the EFS sector to leakage would not be expected if one focussed directly on the effects of competitiveness on EITE industries. International trade in electricity between our model regions is negligible. Nevertheless, there is an indirect effect of increased demand from EITE industries, combined with cost decreases resulting from lower fossil fuel prices. Given the high cost share of fossil fuels in the fossil electricity generation sector, this effect could be as or more significant than input substitution effects.

To gain more insight into these effects, we consider the marginal changes in fossil and carbon-free electricity sector outputs with respect to the participation of Europe (Figure 12) and compare them to those for the participation of North America (Figure 13). We see that in either case, broader participation generally depresses carbon-free electricity output and boosts fossil electricity output. However, changes are relatively larger in some regions than in others and in a few cases, output even moves slightly in the opposite direction. For the two non-coalition regions (OIE and NOE) the changes are significantly larger with respect to European participation than they are with respect to North American participation.

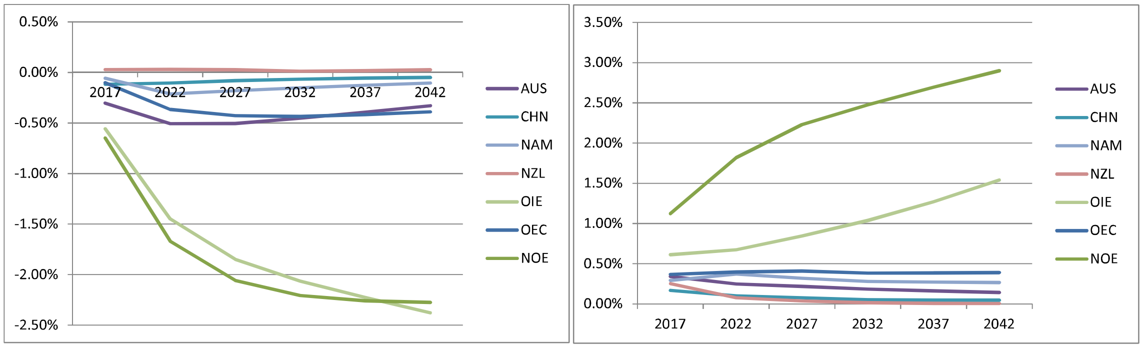

Figure 12 –Marginal changes in other regions' output (as % of baseline output) of carbon-free (left) and fossil (right) electricity generation with respect to the participation of Europe (EUR) in the carbon-pricing coalition.

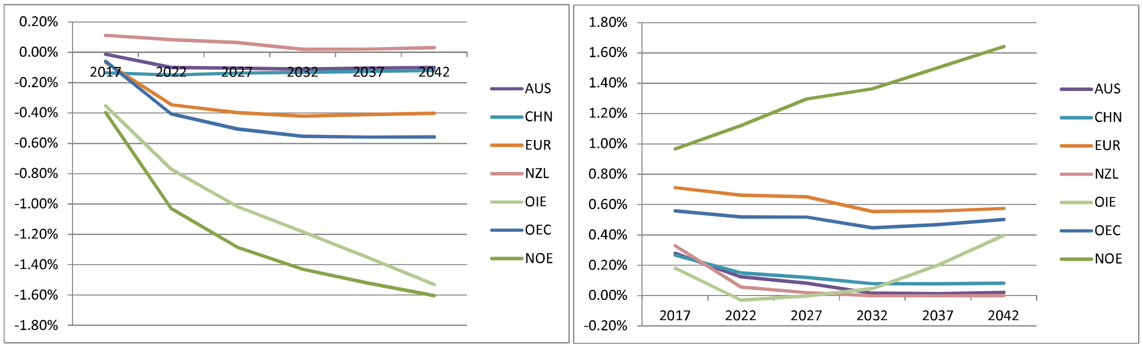

Figure 13 –Marginal changes in other regions' output (as % of baseline output) of carbon-free (left) and fossil (right) electricity generation with respect to the participation of North America (NAM) in the carbon-pricing coalition.

The differences can be interpreted in terms of differences in the effects of regional emissions pricing on a region's excess demand for coal, gas, oil, and petroleum products. For example, a reduction of excess demand for coal in Europe increases the supply of coal to the rest of the world. This increased supply is an important cause of emissions leakage. When we divide the change in excess demand by the change in regional emissions, we find for example that in the 2017 period, this ratio is five times as high for Europe (and seven times as high for the ROE region) as it is for North America. Europe and ROE are net coal importers while the latter is a net coal exporter. Thus, it appears that fossil fuel supply responses play an important role in determining leakage rates, as found in other studies (Burniaux and Oliveira Martins, 2012).

To explain the higher marginal leakage rates of New Zealand when compared to its larger near neighbour Australia, we must again look to structural differences. While the rates are very similar in the first period, in 2042, the marginal rate for New Zealand is 19.5% compared to 14.0% for Australia (see Figures 9 and 5, respectively). The difference is larger if one excludes the negative contributions of domestic (agricultural) leakage. We plot the decomposition these marginal leakage rates by type of leakage and sector in Figure 14. The EMT sector and final consumption (CON) are the main contributors to the difference between the countries' marginal leakage rates. In these cases, much of the differences are due to increases in emissions intensity, but for EMT, increased output within the coalition region is also significant. This may reflect New Zealand's low baseline share of fossil electricity generation (Figure 3). This limits New Zealand's potential to mitigate energy and industrial GHG emissions, making the denominator of the leakage rate smaller. Note also the partial offsetting effects of leakage in the agricultural sector.

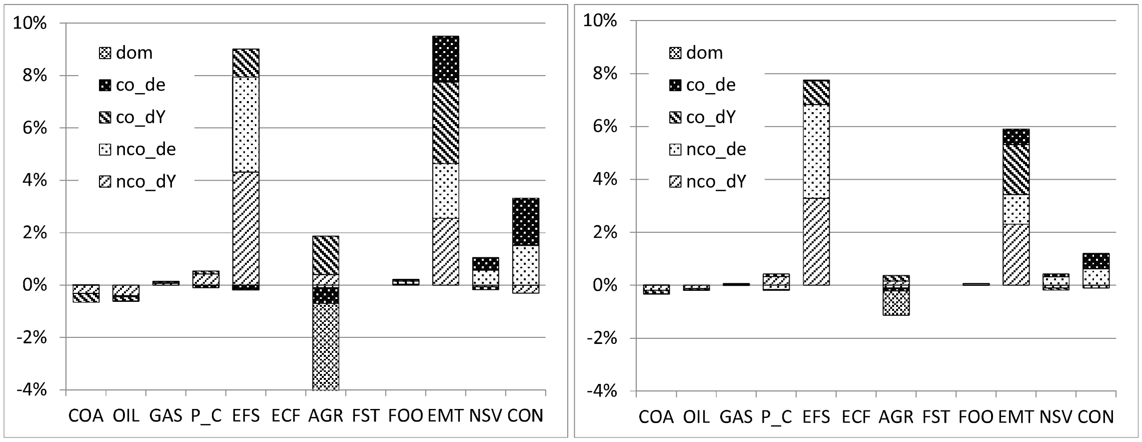

Figure 14 –Contributions to marginal leakage rates in 2042 with respect to participation of New Zealand (left) and Australia (right).

Conclusions

Our results suggest that a broad carbon-pricing coalition consisting of all OECD countries plus China could achieve significant mitigation with low rates of emissions leakage to non-coalition countries. Given that we model a scenario in which carbon tax rates are harmonised internationally and are applied in China as well as in the OECD countries, these results appear consistent with those of many other studies.

Leakage associated with increasing emissions intensity in non-coalition regions is higher in the short term because of the less elastic fossil fuel supply response. However, allowing for lower short-run elasticities of substitution would reduce and might even reverse this effect. In the longer term, leakage rates decline steadily. This is explained by our inclusion in the coalition of China, a very large and fast-growing emitter. Increases of both output and emissions intensities of non-coalition regions contribute almost equally to long-run leakage rates, suggesting that changes in fossil fuel prices remain an important channel for leakage. These increases are partially offset by lower agricultural emissions in the coalition regions, due to direct and indirect effects of pricing energy and industrial emissions and negative income effects.

We find large differences in mitigation potentials and economic costs between regions. Mitigation and impacts on GDP are much larger for China than for any of the OECD regions we model. Amongst the OECD regions, we find that New Zealand has quite low mitigation potential and costs, particularly when compared to its near neighbour, Australia. New Zealand's limited mitigation potential reflects its already high proportion of carbon-free electricity generation as well as our limitation, in this study, of carbon-pricing to energy and industrial emissions. By contrast, Australia is heavily dependent on coal-fired electricity generation.

There are large differences in marginal leakage rates that reflect differences in emissions intensity of production and economic structure but are little influenced by size. Taking the carbon price rather than emissions caps for each region as fixed means that the decision of one country to participate – or not – in the carbon-pricing coalition affects the aggregate emissions of the other coalition countries. An important consideration in this context is that pricing of emissions in other coalition regions reduces leakage in those regions by diminishing the relative importance of fuel prices changes. Marginal leakage rates as defined here could therefore differ significantly in a cap-and-trade scheme yielding identical carbon prices.

In this paper we employed a baseline that accounted only for initial differences in structure and differences over time in rates of GDP growth. We intend to improve these estimates in the future by incorporating in our baseline realistic projections of fossil fuel supply and autonomous trends in energy supply and efficiency. Short-run dynamics also warrant further investigation as they may be sensitive to model structure and parameters that determine effective elasticities of substitution. In this context, better empirical estimates of short- versus long-run elasticities of substitution for energy use would be most valuable.

Acknowledgements

The authors wish to acknowledge funding received from the New Zealand Ministry of Primary Industries' Sustainable Land Management and Adaptation to Climate Change (SLMACC) fund. However, all views expressed in this paper are those of the authors and do not necessarily reflect the views of the Ministry for Primary Industries.

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