Is there a case for carbon-based border tax adjustment? An applied general equilibrium analysis

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ABSTRACT

Growing concern that unilateral greenhouse gas emission reductions could foster carbon leakage and undermine international competitiveness of domestic industry have led a number of EU and US politicians to advocate the use of border-tax adjustments (BTAs) to "level the playing field". Such proposals have so far often been dismissed on administrative feasibility and protectionist grounds, but surprisingly little economic analysis has been performed to assess their actual impacts on leakage, competitiveness and welfare. This paper uses the global recursive-dynamic general equilibrium model ENV-Linkages to fill this gap. Two alternative scenarios are considered under which either the EU alone or Annex- I countries as a whole cut their emissions by 20% by 2020 (and 50% by 2050) relative to 2005 levels. A broad range of checks are performed to assess the robustness of the main results to key model parameters, country coverage, targets and design features of BTAs. Two main conclusions stand out.

First, BTAs are an effective way of reducing carbon leakage, if there is only a small coalition of acting countries, such as, just the EU, because leakage (while typically small) mainly occurs through the competitveness rather than through the fossil fuel price channel in this case. However, the need for, and the effectiveness of BTAs declines rapidly with the size of the coalition, as BTAs address a smaller share of an even smaller rate of leakage.

Second, BTAs entail small welfare losses as a world level. Perhaps more strikingly, they do not necessarily curb the output losses incurred by the domestic energy intensive-industries (EIIs) they are intended to protect in the first place. This is in part because EIIs in the EU and the US make important use of carbon-intensive intermediate inputs produced by these same EIIs in other geographical areas. Another, deeper explanation is that EIIs are ultimately more adversely affected by carbon pricing itself than by any international competitiveness losses.

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1. Introduction

Anthropogenic climate change is a global public bad that calls for a global policy answer. Yet, partly reflecting strong free-riding incentives, the immediate prospects for a global carbon price addressing the negative externality associated with greenhouse gas (GHG) emissions are weak. Policy action is proceeding only gradually, with only some of the main emitting countries taking on binding policy measures. The 2009 Copenhagen Accord confirmed that global climate policy action, if any, will likely be built out of a collection of fragmented domestic commitments. At the same time, growing concern that such unilateral reductions could foster "carbon leakage" and undermine the international competitiveness of domestic industries have led a number of politicians in industrial countries to advocate the use of border-tax adjustments (BTAs) to "level the playing field". In the European Union (EU), BTAs have recently been contemplated notably under the lead of French President Nicolas Sarkozy, and in the United States (US) they have featured prominently in two legislative initiatives put to Congress in 2009. BTAs could take several forms, such as taxing imports or forcing importers to surrender emission allowances under domestic emission trading schemes (ETS). In principle they could also be computed on the basis of alternative measures of carbon content (content of imports or comparable domestic production, direct or direct and indirect – through inputs – content).

The environmental rationale for BTAs is not straightforward, notwithstanding the participation incentives they might provide by punishing free-riding. There is indeed a fairly broad consensus from the computable general equilibrium (CGE) literature that carbon leakage is limited, at least under plausible assumptions about key parameters such as carbon supply and trade elasticities (see in particular Burniaux and Oliveira Martins, 2000), and some papers have even explored the possibility of reverse leakage through endogenous technological change and international technology spillovers to non-mitigating countries (Grubb *et al.,* 2002; Gerlagh and Kuik, 2007).[2] There is a much clearer political economy rationale, however. Even though leakage may be small overall, domestic energy-intensive industries exposed to international competition (EIIs) may still incur sizeable competitiveness and output losses from unilateral emission reduction action, especially in oligopolistic sectors producing an homogenous tradable good (Babikker, 2005; Demailly and Quirion, 2006, 2008a, 2008b). And indeed EIIs have been lobbying hardest for BTAs in both the EU and the US, with the result that some recent BTA proposals focus essentially on these industries.

So far the economic debate on BTAs has mostly centered on administrative feasibility and consistency with WTO rules, and on compatibility with free trade more broadly (De Cendra, 2006; Demaret and Stewardson, 1994; Goh, 2004; Ismer and Neuhoff, 2007; Perez, 2006; Stiglitz, 2006). However, surprisingly little economic analysis has been performed to assess the actual economic effects of BTAs. Based on earlier literature on the equivalence between origin and destination based sales taxes (Dosser, 1968; Krauss and Johnson, 1972, Shibata, 1967) and its implications for the effects of BTAs (Grossman, 1980; Whalley, 1979), Lockwood and Whalley

[2] The focus of this literature, including the present paper, is on leakage across space. Some recent studies have stressed that more leakage might in fact occur across time through an inter-temporal channel. With finite fossil fuel endowments, pricing carbon today and announcing higher prices tomorrow gives carbon producers incentives to raise supply today, possibly leading to an increase rather than a decline in world emissions (Sinn, 2008). This mechanism is found to be even larger under incomplete geographical coverage of carbon pricing (Eichner and Pethig, 2009).

(2008) discuss the economics of carbon-based BTAs. They stress that under a number of restrictive conditions (not least the absence of labour-leisure choice), and provided they apply similarly to all goods, BTAs have only nominal effects, without any real effects on production, consumption and trade. By contrast, because the carbon content of goods differs, carbon-based BTAs distort relative prices and cannot be neutral. As a result, abstracting from their possible environmental effects, BTAs imply a welfare loss relative to a no-domestic-carbon-tax / no-BTA scenario. Whether they also imply a welfare loss relative to a carbon-tax / no-BTA scenario is less clear, as in this case BTAs may partly correct for the distortion associated with applying a carbon tax only to domestic goods. The effects of BTAs are therefore largely an empirical matter. Dong and Whalley (2009) build a small illustrative four-region two-sector CGE model, and find beneficial effects of BTAs on leakage but only small impacts on welfare and production for the EU and the US. This is partly because they assume BTAs to be based only on the direct carbon content of domestic goods, rather than on the (much higher) carbon content of EU and US imports. Mattoo *et al.* (2009) explore a broader range of options using a more detailed CGE framework, and find larger impacts of BTAs in some scenarios. But here again it is a matter of how BTA are modelled. In this paper they are based on the direct plus the total indirect carbon content of imported goods and the tariffs rates are calculated once for all at the starting year.

This paper uses a global recursive-dynamic CGE model, ENV-Linkages, to assess the impacts of BTAs on leakage, competitiveness and welfare. Given the empirical nature of the issue, and the central role played by interactions across countries and sectors through trade and fossil fuel price channels, an applied global CGE framework indeed appears to be the appropriate analytical tool. Two main scenarios are considered under which either the EU alone or Annex-I countries under the Kyoto Protocol (mostly industrialised countries) as a whole cut their emissions by 20% by 2020 relative to 2005 levels. Consistent with recent legislative initiatives and political economy fundamentals, we pay special attention to EIIs throughout the analysis. Importantly, a broad-based sensitivity analysis is performed to assess the robustness of the main results to key model parameters, targets, countries and design features of BTAs.

Two main conclusions stand out. First, BTAs are an effective way of reducing carbon leakage for small coalitions of acting countries such as the EU, because leakage (while typically small) mainly occurs through the international trade rather than through the fossil fuel price channel in this case. However, the need for, and the effectiveness of BTAs declines rapidly with the size of the coalition, as BTAs address a smaller share of an even smaller rate of leakage. Second, the economic effects of BTAs are small. They have negligible welfare effects both worldwide and for countries that implement them. This is not wholly unexpected given that their effects are theoretically ambiguous. Perhaps more strikingly, BTAs do not necessarily curb the output losses incurred by the domestic EIIs they are intended to support in the first place. This is in part because EIIs in the EU and the US make important use of carbon-intensive intermediate inputs produced by these same EIIs in other geographical areas. Another, deeper explanation is that EIIs are ultimately more adversely affected by carbon pricing itself than by any international competitiveness losses.

The rest of this paper proceeds as follows. Section 2 assesses leakage, welfare and competitiveness losses from unilateral emission reduction action under two benchmark scenarios. Section 3 explores the effects of introducing BTAs under these scenarios, and Section 4 performs sensitivity analysis of the main results to key model parameters, targets and design features of BTAs. Section 5 concludes.

2. Two illustrative unilateral emission reduction scenarios

The assessment of the economic effects of BTAs relies in a first step on two benchmark climate policy scenarios, under which either the EU alone or Annex-I countries under the Kyoto Protocol as a whole cut their emissions by 20% by 2020 and by 50% by 2050, relative to 2005 levels. At the 2020 horizon, the former scenario (*scenario EU noBTA*) corresponds in fact to the official EU emission reduction target.[3] The latter scenario (*scenario A1 noBTA*) is more illustrative, and aims at exploring possible differences in the magnitude of leakage and the economic effects of BTAs between smaller and larger coalitions of acting countries. Reflecting the likely magnitude and unpredictability of long-term changes in the structure of the world economy, as well as the very low probability that a small number of countries will act alone over an horizon of several decades anyway, we mainly focus on the 2020 horizon and do not look beyond 2030.

Both scenarios A and B are simulated using the OECD's ENV-Linkages model, a global recursive-dynamic CGE model featuring 12 world regions and 22 sectors, and including both CO_2 and non-CO_2 GHGs. The main features of the model are discussed in Annex 1 and in greater detail in Burniaux and Chateau (2008), while the baseline (no-carbon-price / no-BTA) scenario that underpins it is briefly described in Annex 2 and in full in Duval and de la Maisonneuve (2010). We measure the welfare impacts of policy action relative to baseline using the Hicksian equivalent variation in income to asses changes in real income. These utility-based welfare measures do not incorporate the impacts of climate change, which are not covered in ENV-Linkages. While such impacts are subject to broad uncertainty and are small anyway at the 2020 horizon of this paper, this should be borne in mind when interpreting the results from the welfare analyses performed below. Throughout the analysis we also pay special attention to EIIs, which include here chemicals, metallurgic, other metal, iron and steel industry, paper and mining products.

The effects of both scenarios on leakage, real income (Hicksian equivalent variation) and the output of EIIs are presented in Table 1. Leakage is found to be small and to decline with coalition size, reaching just 6 ½ % of the decline in EU emissions by 2020 in *scenario EU noBTA*, and 4 ½ % of the decline in Annex-I emissions in *scenario A1 noBTA*.[4] Moreover, it is not only the magnitude but also the nature of leakage that changes with the size of the coalition. Indeed leakage can arise through two main channels: the international trade channel, as carbon-intensive industries in acting countries lose market shares to their foreign competitors and/or relocate capital in non-acting countries; the fossil fuel price channel, as emission reduction efforts in acting countries lower world demand for fossil fuels, thereby inducing a price decline that triggers greater fossil fuel use and higher GHG emissions in non-participating countries. The wider the country coverage, the smaller the market share losses affecting EIIs in participating countries (the

[3] The EU has indicated that this target could be raised from 20% to 30% if other countries took on "comparable efforts".

[4] Note that the lower leakage rate in *scenario A1 noBTA* compared with *scenario EU noBTA* is not entirely straightforward *a priori*, because the 20% emission reduction objective under both scenarios implies a larger absolute cut (in giga tons CO_2 equivalent, Gt CO_2-eq) is larger than in the former.

international trade channel of leakage), but the larger the impact of policy action on international fossil fuel prices (the fossil fuel price channel of leakage).

Table 1. Unilateral Emission reduction scenarios : 20% cut in 2020 and 50% in 2050 relative to 2005 levels for EU alone (*scenario EU noBTA*) or Annex-I countries (*scenario A1 noBTA*)

Policy Scenario	Carbon tax (USD/t CO_2)	leakage rate (%)	Equivalent variation in income			EII output			World GHG emissions
			World	non-acting countries	acting countries	World	non-acting countries	acting countries	
% change in 2020 with respect to the baseline									
Scenario EU noBTA	20.9	3.8	-0.1	0.0	-0.3	0.0	0.1	-0.4	-1.2
Scenario A1 noBTA	43.3	4.4	-0.6	-0.3	-0.8	-0.4	0.9	-1.5	-8.6
% change in 2030 with respect to the baseline									
Scenario EU noBTA	61.3	7.9	-0.4	-0.1	-1.4	-0.2	0.2	-2.2	7.9
Scenario A1 noBTA	73.6	5.9	-1.2	-0.5	-1.6	-0.9	1.1	-3.2	5.9

The negative welfare impact of the target is smaller for the EU (*scenario EU noBTA*) than for Annex-I countries as a whole (*scenario A1 noBTA*), reflecting the higher carbon intensity of the latter group of countries. Also, the welfare effects of both scenarios become larger by 2030, as the target becomes more binding and the carbon price increases. As would be expected, qualitatively similar, but quantitatively larger impacts are found for the output of EIIs.

3. The impact of BTAs on carbon leakage, the output of EIIs and welfare

We now simulate the impacts of implementing a BTA under the two benchmark scenarios. BTAs should in principle apply to the actual carbon content of imported goods, rather than to the carbon content of comparable domestic goods. Therefore we retain the former set up, although the latter is also analysed in section 4 as it might be easier to implement in practice. Another issue is the extent to which BTAs would apply not only to the direct carbon content of goods but also to their indirect content, *i.e*. to the carbon content of the inputs used to produce these goods. While in theory they should (and could be simulated with ENV-Linkages as in Mattoo *et al.* (2009)), in practice calculating the full indirect carbon content of goods is likely to be impossible, especially given the length and complexity of valued added chains in an increasingly globalised production process. Therefore we consider here two more realistic alternative, namely BTAs applied either only to the direct carbon content of (imported) goods (*Scenario A1 noBTA*TAdir) or to the direct and indirect content *via* the carbon content of electricity inputs (*Scenario A1 noBTA*TAind).

The results are presented in Table 2. BTAs appear to be an effective way for small coalitions to reduce the carbon leakage from their unilateral emission reduction measures, but their effectiveness declines rapidly with coalition size. Indeed the (limited) leakage problem is fully addressed in the EU case (*scenario EU noBTA*),[5] but less so when a larger coalition such as

[5] The EU is even found to experience "negative leakage" once BTAs are implemented. This is because the supply of coal is more elastic than that of crude oil in the benchmark calibration of ENV-Linkages, making coal relatively more

Annex I countries takes action (*scenario A1 noBTA*). This is primarily because under smaller coalitions, leakage arises comparatively more from international competitiveness losses than through a decline in world fossil fuel prices, making BTAs a more effective tool since they address the former but not the latter channel.

By contrast, the economic effects of BTAs are found to be fairly small overall in both scenarios, despite the fact that the unilateral emission reduction scenarios considered here may if anything be seen as relatively ambitious.[6] BTAs yield small positive welfare gains for acting countries, which at the world level are roughly offset by small losses in the rest of the world. Similar results are obtained at both the 2020 and 2030 horizons even though the stringency of the target differs across these dates, as shown by the difference in carbon prices. As noted above, negligible welfare effects from BTAs in the countries that implement them are not entirely unexpected from theory, as their impact is *a priori* ambiguous and driven by the *difference in* – not the level of – the tariffs applied across goods[7].

Perhaps more surprisingly, despite some effectiveness in reducing leakage, BTAs are not found to curb the output losses of EIIs (relative to a carbon tax/no BTA scenario). The output losses incurred by EIIs in both scenarios are roughly unchanged when the direct carbon content of imports is subject to a border tariff, and even increase when both the direct and indirect contents are affected. This is in part because several factors contribute to offset the positive output effects of the market share gains associated with BTAs: first and foremost, because domestic EIIs in industrialised countries rely heavily on imported inputs produced by EIIs at a different level of the value added chain in emerging countries, BTAs increase the production costs of domestic EIIs; second, realistic but incomplete forms of BTAs such as those considered here, which do not cover the full indirect carbon content of imports, do not fully address the competitiveness losses of domestic EIIs; third, and least importantly, the presence of BTAs induces a slight increase in the carbon price to meet the domestic emission target, which further increases the production costs of EIIs. However, as will become apparent in Section 4 below, the single most important factor behind the lack of effectiveness of BTAs to support domestic EIIs is that these industries are ultimately more adversely affected by carbon pricing itself than by any international competitiveness losses.

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expensive in world international markets when emission reduction measures – both direct and indirect such as BTAs – are taken by a reasonably large area such as the EU. This induces a substitution away from more carbon-intensive coal in non-participating countries, and therefore a decline in their emissions that amounts to negative carbon leakage.

[6] While a 20% reduction in GHG emissions corresponds to the official EU target, it is significantly more ambitious than the targets announced so far by Annex I countries as a whole, which amounted to a 5% to 10% reduction in the wake of the "Copenhagen Accord" signed at the UNFCCC 15th Conference of Parties in Copenhagen in December 2009 (OECD, 2009).

[7] Notice that OECD(2009) presented GDPs changes associated with scenarios instead of welfare gains. GPDs effects seem also negligible but negative. Terms of trade and international trade changes explain this differences between GDP and equivalent variantion in income differences.

Table 2. Unilateral Emission reduction scenarios with carbon-based border tax

Policy Scenario	Carbon tax (USD/t CO_2)	leakage rate (%)	Equivalent variation in income			EII output			World GHG emissions
			World	non-acting countries	acting countries	World	non-acting countries	acting countries	
% change in 2020 with respect to the baseline									
Scenario EU noBTA	20.9	3.8	-0.1	0.0	-0.3	0.0	0.1	-0.4	-1.2
Scenario EU BTA dir	21.9	-2.2	-0.1	0.0	-0.2	-0.1	0.1	-0.5	-1.3
Scenario EU BTA ind	22.2	-4.0	-0.1	-0.1	-0.2	-0.1	0.0	-0.4	-1.3
Scenario A1 noBTA	43.3	4.4	-0.6	-0.3	-0.8	-0.4	0.9	-1.5	-8.6
Scenario A1 BTA dir	43.5	2.0	-0.6	-0.5	-0.7	-0.5	0.8	-1.6	-8.9
Scenario A1 BTA ind	43.4	1.1	-0.6	-0.6	-0.6	-0.5	0.6	-1.5	-8.9
% change in 2030 with respect to the baseline									
Scenario A	61.3	7.9	-0.4	-0.1	-1.4	-0.2	0.2	-2.2	7.9
Scenario A BTAdir	62.9	1.0	-0.4	-0.1	-1.2	-0.3	0.2	-2.5	1.0
Scenario A BTA ind	63.4	-1.4	-0.4	-0.2	-1.1	-0.3	0.1	-2.5	-1.4
Scenario B	73.6	5.9	-1.2	-0.5	-1.6	-0.9	1.1	-3.2	5.9
Scenario B BTAdir	73.7	3.4	-1.2	-0.8	-1.5	-1.1	0.9	-3.4	3.4
Scenario B BTA ind	73.7	2.2	-1.3	-1.0	-1.4	-1.2	0.6	-3.3	2.2

4. Generalisation of the results and sensitivity analysis

This section assesses the extent by which these results can be generalized to other OECD countries and alternative ways of implementing the BTAs. It also verifies the robustness of these results to alternative metrics of real income changes and changes in the values of some critical parameters.

The first panel of Table 3 reports impacts of BTAs in the context of unilateral action by the USA (scenarios US noBTA and US BTA ind) and Japan (scenarios JPN noBTA and JPN BTA ind). While the US BTAs only yield a modest reduction of the carbon leakage[8] – from 12 to 9% in 2030, the other results on real income and EIIs outputs are in line with the outcome of the benchmark scenarios. The BTAs imply little changes for mitigation costs and are ineffective in reducing the output losses incurred by EIIs, partly because any attempt to protect domestic EIIs requires a higher carbon price to meet the emission constraints.

The second panel of Table 3 examines the consequences of alternative ways of implementing BTAs. Some analyses assume that the BTAs would be based on domestic rather than imported carbon contents, arguing that this would improve the feasibility of BTAs in practice. Using domestic carbon contents in the two benchmark scenarios for the EU and the Annex I countries (scenarios EU BTAind dom and A1 BTAind dom in Table 3) shows a much smaller reduction of carbon leakages. In both cases, domestic carbon contents in acting countries are generally lower than imported ones as these countries use fossil fuels relatively more efficiently and this results into smaller BTAs. While the environmental effectiveness of applying BTAs on this basis is considerably reduced, the economic costs in terms of real income and EIIs output losses are unchanged or even higher for acting countries.

[8] Reflecting the fact that the US economy is relatively less dependent on trade and therefore the smaller weight of the competitiveness component in the leakage generated by the US action.

Table 3. Impact of Border Tax Adjustments under alternative implementation assumptions.

Policy scenario		Carbon tax (USD/t CO_2)	leakage rate (%)	Equivalent variation in income			EII output			World GHG emissions
				World	non-acting countries	acting countries	World	non-acting countries	acting countries	
				% change in 2030 with respect to the baseline						
Sensitivity to the country										
US noBTA	USA acting alone	73	11.8	-0.4	-0.1	-1.2	-0.3	0.6	-4.6	-5.2
US BTA ind	USA acting alone + BTA	75	8.6	-0.4	-0.2	-1.0	-0.4	0.4	-4.6	-5.4
JPN noBTA	Japan acting alone	30	12.5	-0.1	0.0	-0.4	0.0	0.1	-1.4	-0.5
JPN BTA ind	Japan acting alone + BTA	31	5.5	-0.1	0.0	-0.3	0.0	0.1	-1.4	-0.6
Alternative implementation										
EU BTAind dom	EU acting alone + BTA based on domestic carbon content	62	5.2	-0.4	-0.1	-1.3	-0.3	0.2	-2.5	-2.5
A1 BTAind dom	Annex I countries acting alone + BTA based on domestic carbon conten	74	4.5	-1.3	-0.7	-1.6	-1.1	1.1	-3.6	-12.8
EU BTAind sub	EU acting alone + BTA exempting exports	64	-0.9	-0.4	-0.1	-1.3	-0.3	0.2	-2.3	-2.6
A1 BTAind sub	AnnexI countries acting alone + BTA exempting exports	75	3.6	-1.3	-0.7	-1.6	-1.2	0.8	-3.4	-12.9
EU noBTA CO2	EU acting alone with CO_2 only	79	13.5	-0.4	-0.1	-1.7	-0.2	0.2	-2.1	-1.7
EU BTAind CO2	EU acting alone with CO_2 only + BTA	82	0.9	-0.5	-0.2	-1.4	-0.3	0.2	-2.5	-1.9
A1 noBTA CO2	AnnexI countries acting alone with CO_2 only	86	9.1	-1.2	-0.5	-1.6	-0.9	1.3	-3.3	-9.8
A1 BTAind CO2	AnnexI countries acting alone with CO_2 only + BTA	87	4.7	-1.3	-1.0	-1.5	-1.2	0.9	-3.4	-10.4
EU BTAind diag	EU acting alone with BTA and exempting diagonal imported input	64	-1.6	-0.4	-0.2	-1.1	-0.3	0.1	-1.9	-2.6
A1 BTAind diag	A1 countries acting alone with BTA and exempting diagonal imported inp	74	2.2	-1.3	-1.0	-1.4	-1.1	0.5	-3.0	-13.1

Source: OECD ENV-Linkages model (spring 2010 baseline)

BTAs on imports alone only partly address the issue of competitiveness in acting countries as they fail to compensate for the competitiveness losses that EIIs would incur on their export markets. A symmetrical treatment of EIIs imports and exports would in principle guarantee a more complete protection of their competitiveness; this would involve BTAs on imports together with exempting EIIs exports from any increase of the carbon price domestically. While having little impact on EIIs output losses (scenarios EU BTAind sub and A1 BTAind sub in Table 3), such a measure would increase the economic losses incurred by acting countries because, as it amounts to reducing the coverage of carbon pricing, it requires a higher carbon price to meet the emissions target. As carbon leakages tend to increase in response to a higher carbon price, the environmental effectiveness overall is reduced, although slightly.

Similarly, restricting mitigation to CO2 emissions from fuel combustion only (rather than a comprehensive mitigation across all greenhouse gases) requires much higher taxes (scenarios EU noBTA CO2 and A1 noBTA CO2 in Table 3) and implies significantly higher leakage rates: leakage rates calculated for all GHGs in 2030 reach 14% for the EU and 9% for the Annex I compared with 8% and 6% respectively if mitigation involves all GHGs. This illustrates the role of CO2 and the importance of the world energy markets in generating carbon leakages. The impact of BTAs (scenarios EU BTAind CO2 and A1 BTAind CO2) in the context of CO2 mitigation only is in line with previous results: namely a reduction of the leakage rate, mostly significant in the case of the EU, a slight reduction of the real income loss in the acting countries compensated by increasing losses in other countries and no reduction of the output losses reported by EIIs in acting countries, on the contrary.

The two last scenarios (scenarios EU BTAind diag and A1 BTAind diag) at the bottom of Table 3 show that the only way a carbon-based BTA can soften somewhat the output loss incurred by the EIIs in the acting countries (the EU and Annex I countries) is to exempt from the BTA their imported input of EIIs products originating from trading partners. This would reduce the EIIs output loss to 1.9% in 2030 in the EU (compared with 2.2% in the corresponding benchmark scenario) and 3% in the Annex I countries (compared with 3.3%). These differences are marginal and this exemption does not affect the environmental effectiveness of the policy.

Finally, Table 4 illustrates that these results are reasonably robust to alternative values of some key parameters. The amount of leakage in the case of unilateral action is clearly dependent of the elasticity of fossil fuel supply at the world level. A more (less) elastic supply of fossil fuels implies lower (higher) leakages. The effectiveness of BTAs in reducing carbon leakages is substantially reduced in case of less elastic fossil fuel supply; this is particularly the case in the scenario of unilateral action by Annex I countries where, with lower fossil fuel supply elasticities, BTAs only reduce the leakage rates from 9.5% to 8% in 2030. The degree of product differentiation on the world trade market also influences the amount of carbon leakages. If products from different origins are more substitutable (as simulated by raising the values of the Armington elasticities), carbon leakages are higher (for instance, 9% in *scenario EU noBTA* in Table 5 compared with 8% in the corresponding scenario in Table 2) and the loss of competitiveness incurred by EIIs results into a higher output loss. But the environmental and economic impact of the BTAs remain roughly unchanged.

5. Conclusion

As industrialised countries increasingly implement or consider unilateral constraints on domestic GHG emissions, the political momentum for BTAs to address carbon leakage and "level the playing field" between their EIIs and their unconstrained foreign competitors can be expected to grow. A small body of recent economic research that builds on earlier literature on border adjustments points to ambiguous and probably small welfare effects of BTAs *a priori*, but this has yet to be backed by fully-fledged applied analyses. This paper began to fill this gap by using a global recursive-dynamic CGE model, ENV-Linkages, to assess the potential impacts of BTAs on leakage, competitiveness and welfare. Illustrative unilateral emission reduction scenarios with and without BTAs are explored, and extensive sensitivity analysis is performed assess the robustness of the results to targets, countries, design features of BTAs and key parameters such as fossil fuel supply or international trade elasticities. A robust finding across all simulations is that BTAs have only small welfare effects. They have also typically no beneficial impact on the output of the EIIs they are intended to support in the first place. BTAs primarily reduce the demand for, and thereby the output of the foreign competitors of domestic EIIs, leading to a mechanical increase in the global market share of domestic EIIs. However this does not bring any output gains since the positive impact of competitiveness gains is typically offset by a rise in production costs, and both effects are small anyway compared with the output losses associated with the existence of a carbon price. BTAs are more effective at reducing carbon leakage, and the environmental gains from lower global emissions are not factored into the welfare analysis performed in this paper. However, such gains are unlikely to radically alter our conclusions, as the unilateral targets considered here and those that can be expected to be adopted in practice amount to a modest mitigation of worldwide emissions, a small share of which is subject to leakage. Overall, the ongoing debate on BTAs appears to be largely overdone.

Table 4. Sensitivity analysis with respect to the values of key parameters

Policy scenario		Carbon tax (USD/t CO_2) in 2030	Leakage rate (%) in 2030	% change in 2030 with respect to the baseline						
				Real Income			EII output			World GHG emissions
				World	non-acting countries	acting countries	World	non-acting countries	acting countries	
Sensitivity to price elasticity of fuel supply										
EU noBTA	Fossil fuel supply more elastic	59	5.2	-0.4	-0.1	-1.5	-0.2	0.2	-2.2	-2.5
EU BTA ind	Fossil fuel supply more elastic	61	-4.1	-0.4	-0.2	-1.2	-0.4	0.1	-2.4	-2.7
EU noBTA	Fossil fuel supply less elastic	66	13.6	-0.3	-0.1	-1.4	-0.2	0.3	-2.3	-2.2
EU BTA ind	Fossil fuel supply less elastic	68	4.3	-0.4	-0.2	-1.1	-0.3	0.2	-2.6	-2.5
A1 noBTA	Fossil fuel supply more elastic	70	4.2	-1.3	-0.5	-1.7	-1.0	1.0	-3.2	-12.9
A1 BTA ind	Fossil fuel supply more elastic	70	2.8	-1.3	-0.7	-1.7	-1.2	0.9	-3.6	-13.0
A1 noBTA	Fossil fuel supply less elastic	80	9.5	-1.1	-0.4	-1.4	-0.9	1.3	-3.3	-12.1
A1 BTA ind	Fossil fuel supply less elastic	81	8.1	-1.1	-0.6	-1.4	-1.1	1.3	-3.7	-12.3
Sensitivity to Armington Elasticities (AE)										
EU noBTA	low AE for manufacturing goods in all countries	62	7.5	-0.4	-0.1	-1.4	-0.2	0.2	-2.0	-2.4
EU BTA ind	low AE for manufacturing goods in all countries	64	-2.1	-0.4	-0.2	-1.1	-0.4	0.1	-2.4	-2.6
EU noBTA	high AE for manufacturing goods in all countries	61	8.8	-0.4	-0.1	-1.5	-0.3	0.3	-2.5	-2.4
EU BTA ind	high AE for manufacturing goods in all countries	63	-0.4	-0.4	-0.2	-1.2	-0.4	0.2	-2.6	-2.6
A1 noBTA	low AE for manufacturing goods in all countries	74	5.3	-1.2	-0.6	-1.5	-1.0	0.8	-3.0	-12.7
A1 BTA ind	low AE for manufacturing goods in all countries	74	1.5	-1.3	-1.1	-1.4	-1.3	0.4	-3.3	-13.2
A1 noBTA	high AE for manufacturing goods in all countries	73	6.9	-1.2	-0.4	-1.6	-0.9	1.6	-3.7	-12.5
A1 BTA ind	high AE for manufacturing goods in all countries	73	3.2	-1.3	-0.9	-1.5	-1.2	0.9	-3.5	-13.0

Source: OECD ENV-Linkages model (spring 2010 baseline)

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Annex1. Overview of the OECD ENV-linkages model

The OECD ENV-Linkages General Equilibrium model is the successor to the OECD GREEN model for environmental studies, which was initially developed by the OECD Economics Department (Burniaux, et al. 1992) and is now hosted at the OECD Environment Directorate. GREEN was originally used for studying climate change mitigation policy and culminated in Burniaux (2000). It was developed into the Linkages model, and subsequently became the JOBS/Polestar that was used to help underpin analysis for the book OECD(2001). A version of that model is also currently in use at the World Bank for research in global economic development issues. Previous works using extensively the model include two books : OECD (2008) and OECD(2009). Exploration of some of the model's properties and some sensitivity analysis is reported in OECD (2006).

1. The structure of the model

Key features

The ENV-Linkages model is a recursive dynamic neo-classical general equilibrium model. It is a global economic model built primarily on a database of national economies. In the version of the model used here, the world economy is divided in 12 countries/regions, each with 25 economic sectors (Tables 1 and 2), including five different technologies to produce electricity. Each of the 12 regions is underpinned by an economic input-output table (usually sourced from national statistical agencies). The database has been built and maintained at Purdue University by the Global Trade Analysis Project (GTAP) consortium. A fuller description of the database can be found at Dimaranan (2006). Those tables identify all the inputs that go into an industry, and identify all the industries that buy specific products.

Table 3. ENV-Linkages model sectors

Labels	Description
1) Rice	Paddy rice: rice, husked and in the husk.
2) Other crops	Wheat: wheat and meslin
	Other Grains: maize (corn), barley, rye, oats, other cereals
	Veg & Fruit: vegetables, fruits, fruit and nuts, potatoes, cassava, truffles.
	Oil Seeds: oil seeds and oleaginous fruits; soy beans, copra
	Cane & Beet: sugar cane and sugar beet
	Plant fibers: cotton, flax, hemp, sisal and other raw vegetable materials used in textiles
	Other Crops
3) Livestock	Cattle: cattle, sheep, goats, horses, asses, mules, and hinnies; and semen thereof
	Other Animal Products: swine, poultry and other live animals; eggs, in shell, natural honey, snails
	Raw milk
	Wool: wool, silk, and other raw animal materials used in textile
4) Forestry	Forestry: forestry, logging and related service activities
5) Fisheries	Fishing: hunting, trapping and game propagation including related service activities, fishing,
	fish farms; service activities incidental to fishing
6) Crude Oil	Parts of extraction of crude petroleum & service activities incidental to oil extraction excl. surveying
7) Gas extraction and	Pars of extraction of natural gas & service activities incidental to gas extraction excl. surveying

distribution	
	distribution of gaseous fuels through mains; steam and hot water supply
8) Fossil Fuel Based Electricity	Coal, Coal gases, Natural gases and oil fired electricity (production, collection and distribution)
9) Hydro and Geothermal electricity	Hydroelectric power and Geothermal electricity
10) Nuclear Power	Nuclear Power
11) Solar& Wind electricity	Solar, Wind, Wave and Tide Electricity
12) Renewable combustibles and waste electricity	wood, wood waste, other solid waste ; industrial waste ; municipal waste ; biogas ; liquid biofuels & waste
13) Petroleum & coal products	Petroleum & Coke: coke oven products, refined petroleum products, processing of nuclear fuel
14) Food Products	Cattle Meat: fresh or chilled meat and edible offal of cattle, sheep, goats, horses, asses, mules
	Pig meat and offal. Preserves and preparations of meat, meat offal or blood, flours
	Vegetable Oils: crude and refined oils of soya-bean, maize, olive, sesame, groundnut, olive seeds
	Milk: dairy products
	Processed Rice: rice, semi- or wholly milled
	Sugar
	Other Food: prepared and preserved fish or vegetables, fruit & vegetable juices, prepared fruits, flours,
	Beverages and Tobacco products
15) Other Mining	Other Mining: mining of metal ores, uranium, gems. other mining and quarrying
16) Non-ferrous metals	Non-Ferrous Metals: production and casting of copper, aluminum, zinc, lead, gold, and silver
17) Iron & steel	Iron & Steel: basic production and casting
18) Chemicals	Chemical Rubber Products: basic chemicals, other chemical products, rubber and plastics products
19) Fabricated Metal Products	Fabricated Metal Products: Sheet metal products, but not machinery and equipment
20) Paper & Paper Products	Paper & Paper Products: includes publishing, printing and reproduction of recorded media
21) Non-Metallic Minerals	Non-Metallic Minerals: cement, plaster, lime, gravel, concrete
22) Other Manufacturing	Textiles: textiles and man-made fibers
	Wearing Apparel: Clothing, dressing and dyeing of fur
	Leather: tanning and dressing of leather; luggage, handbags, saddlery, harness and footwear
	Other Transport Equipment: Manufacture of other transport equipment
	Electronic Equipment: office, accounting and computing, radio, television and communication equipment
	Other Machinery & Equipment: electrical machinery, medical, precision and optical, watches
	Other Manufacturing: includes recycling
	Motor Vehicles: cars, lorries, trailers and semi-trailers
	Lumber: wood and products of wood and cork, except furniture; articles of straw and plaiting materials
23) Transport services	Other Transport: road, rail ; pipelines, auxiliary transport activities; travel agencies
	Water transport
	Air transport
24) Services	Trade: all retail sales; wholesale trade and commission trade; hotels and restaurants;
	repairs of motor vehicles and personal and household goods ;

	Water: collection, purification and distribution
	Retail sale of automotive fuel
	Communications: post and telecommunications
	Other Financial Intermediation: includes auxiliary activities but not insurance and pension funding
	Insurance: includes pension funding, except compulsory social security
	Other Business Services: real estate, renting and business activities
	Recreation & Other Services: recreational, cultural and sporting activities, other service activities;
	private households with employed persons
	Other Services (Government): public administration and defense; compulsory social security,
	education, health and social work, sewage and refuse disposal, sanitation and similar activities,
	activities of membership organizations n.e.c., extra-territorial organizations and bodies
25) Construction & Dwellings	Construction: building houses factories offices and roads
	Dwellings: ownership of dwellings (imputed rents of houses occupied by owners)

Table 4. Table 2. ENV-Linkages model regions

ENV-Linkages regions	GTAP countries/regions
1) Australia, New Zealand	Australia, New Zealand
2) Japan	Japan
3) Canada	Canada
4) United States	United States
5) European Union and EFTA	Austria, Belgium, Denmark, Finland, Greece, Ireland, Luxembourg, Netherlands, Portugal, Sweden, France, Germany, United Kingdom, Italy, Spain, Switzerland, Rest of EFTA, Czech Republic, Slovakia, Hungary, Poland, Romania, Bulgaria, Cyprus, Malta, Slovenia, Estonia, Latvia, Lithuania
6) Brazil	Brazil
7) China	China, Hong Kong
8) India	India
9) Russia	Russian Federation
10) Oil producing countries	Indonesia, Venezuela, Rest of Middle East, Islamic Republic of Iran, Rest of North Africa, Nigeria
11) Rest of Annex 1 countries	Croatia, Rest of Former Soviet Union
12) Rest of the world	Korea, Taiwan, Malaysia, Philippines, Singapore, Thailand, Viet Nam, Rest of East Asia, Rest of Southeast Asia, Cambodia, Rest of Oceania, Bangladesh, Sri Lanka, Rest of South Asia, Pakistan, Mexico, Rest of North America, Central America, Rest of Free Trade Area of Americas, Rest of the Caribbean, Colombia, Peru, Bolivia, Ecuador, Argentina, Chile, Uruguay, Rest of South America, Paraguay, Turkey, Rest of Europe, Albania, Morocco, Tunisia, Egypt, Botswana, Rest of South African Customs Union, Malawi, Mozambique, Tanzania, Zambia, Zimbabwe, Rest of Southern African Development Community, Mauritius, Madagascar, Uganda, Rest of Sub-Saharan Africa, Senegal, South Africa.

Production

All production in ENV-Linkages is assumed to operate under cost minimisation with an assumption of perfect markets and constant return to scale technology. The production technology is specified as nested CES production functions in a branching hierarchy. Figure 1 illustrates the typical nesting of the model's sectors (some sectors, like agriculture have a different nesting). The nesting of the electricity production is slightly different and is reported in Figure 2. In Figure 1 and 2, each node represents a constant elasticity of substitution (CES) production function. This gives marginal costs and represents the different substitution (and complementarity) relations across the various inputs in each sector. Each sector uses intermediate inputs – including energy inputs - and primary factors (labour and capital). In some sectors, primary factors include natural resources, *e.g.* trees in forestry, land in agriculture, etc.

In a way similar to Hyman *et al.* (2002), the top-level production nest considers final output as a composite commodity combining emissions of non-CO_2 gases and the production of the sector net of these emissions. In sectors that do not emit non-CO_2 gases, the corresponding emission rate is set equal to zero. For the purpose of calibration, these non-CO_2 gases are valuated using an arbitrary very low carbon price. The following non-CO_2 emission sources are considered: *i)* methane from rice cultivation, livestock production (enteric fermentation and manure management), coal mining, crude oil extraction, natural gas and services (landfills); *ii)* nitrous oxide from crops (nitrogenous fertilizers), livestock (manure management), chemicals (non-combustion industrial processes) and services (landfills); *iii)* industrial gases (SF6, PFC's and HFC's) from chemicals industry (foams, adipic acid, solvents), aluminum, magnesium and semi-conductors production. The values of the substitution elasticities are calibrated such as to fit to marginal abatement curves available in the literature on alternative technology options (US-EPA, 2006b).

The second-level nest considers the gross output of sector (net of GHGs) as a combination of aggregate intermediate demands and a value-added bundle, including energy. For each good or service, output is produced by different production streams which are differentiated by capital vintage (old and new). Capital that is implemented contemporaneously is new – thus investment impacts on current-period capital; but then becomes old capital (added to the existing stock) in the subsequent period. Each production stream has an identical production structure, but with different technological parameters and substitution elasticities. Letting $X_{i,v}$ represents gross output of sector i (net of GHGs) using capital of vintage v, the equations representing production are derived from first order conditions [1]-[3] of the firm's profit maximisation objective.

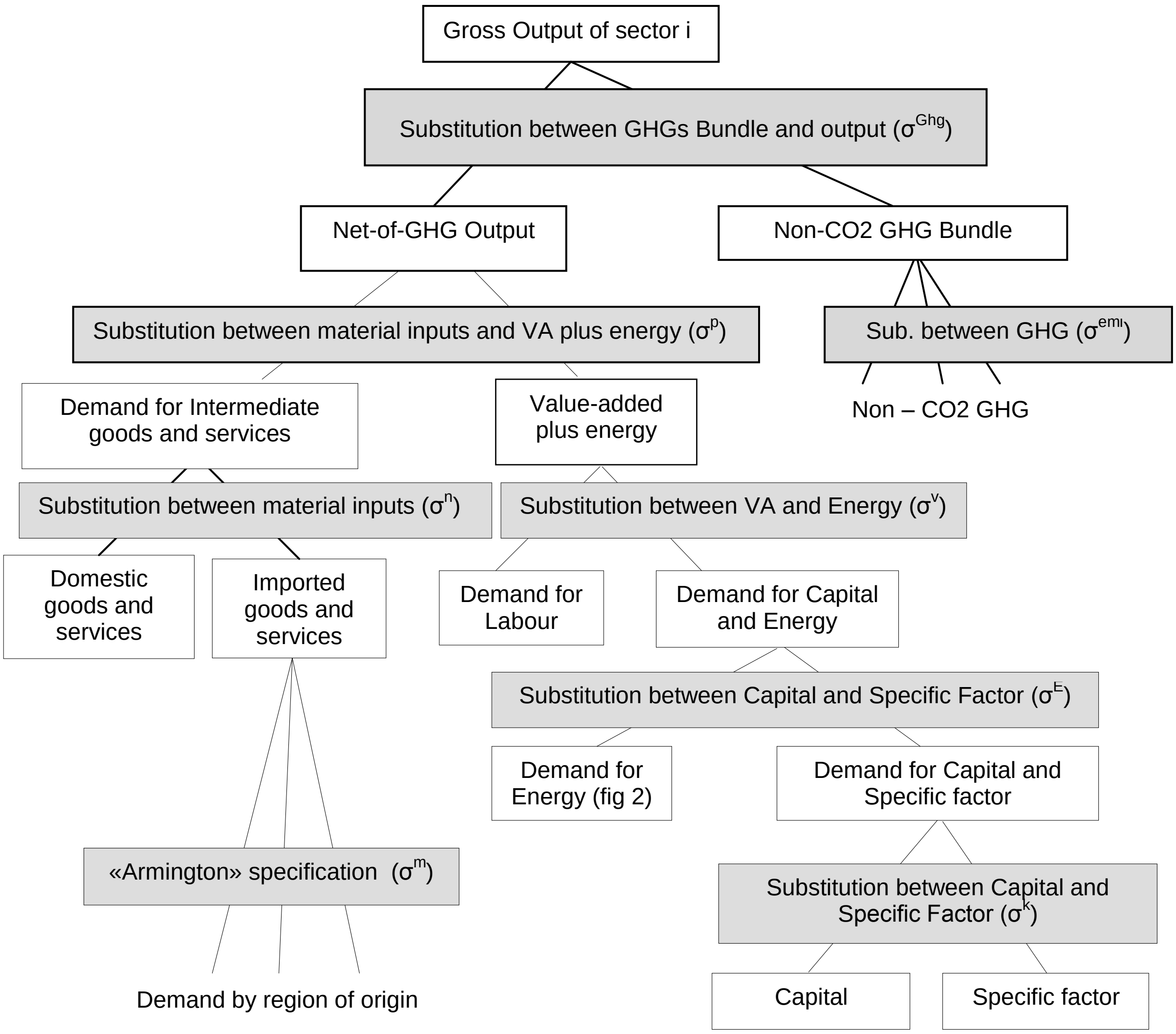
$$INT_i = \sum_v \alpha_{i,v}^{INT} \times A_{i,v}^{\sigma_{i,v}^p - 1} \times \left(\frac{VC_{i,v}}{P_i^{INT}} \right)^{\sigma_{i,v}^p} \times X_{i,v} \tag{1}$$

$$VA_{i,v} = \alpha_{i,v}^{VA} \times A_{i,v}^{\sigma_{i,v}^p - 1} \times \left(\frac{VC_{i,v}}{P_i^{VA}} \right)^{\sigma_{i,v}^p} \times X_{i,v} \tag{2}$$

$$VC_{i,v} = \frac{1}{A_i} \times \left[\alpha_{i,v}^{INT} \left(P_i^{INT} \right)^{1-\sigma_{i,v}^p} + \alpha_{i,v}^{VA} \left(P_i^{VA} \right)^{1-\sigma_{i,v}^p} \right]^{(1/(1-\sigma_{i,v}^p))} \tag{3}$$

where *INT* is the intermediate demand bundle (P^{INT} its price), *VA* represents value-added (P^{VA} its price), *VC* is unit variable cost of producing one unit of net of GHGs output (average costs include the cost of capital), *A* is a technical change term. In order to determine the industry-wide cost that includes both capital vintages, there is an averaging (weighted) of variable costs across the two vintages.

Figure 1. Structure of production in ENV-Linkages



Note: see Table 3 for parameter values

In each period, the supply of primary factors (*e.g.* capital, labour, land and natural resources) is usually predetermined. On the right hand side of the tree in Figure 1 value-added[9] is shown as being composed of a labour input [4] along with a composite capital/energy bundle [5]:

[9] The valued-added bundle is specified as a CES combination of labour and a broad concept of capital. In the "crop" production sector, this capital is itself a CES combination of fertilizer and another bundle of capital-land-energy. The intention of this specification is to reflect the possibility of substitution between intensive and extensive agriculture. In the "livestock" sector, substitution possibilities are between bundles of land and feed, on the one hand, reflecting a similar choice between extensive and intensive livestock production, and of capital-energy-labour bundle, on the other hand.

$$L_i = \sum_v \alpha_{i,v}^{L} \times \lambda_i^{\sigma_{i,v}^{V}-1} \times \left(\frac{P_{i,v}^{VA}}{W_i}\right)^{\sigma_{i,v}^{V}} \times VA_{i,v}$$

[4]

$$KE_{i,v} = \alpha_{i,v}^{KE} \times \left(\frac{P_{i,v}^{VA}}{P_{i,v}^{KE}}\right)^{\sigma_{i,v}^{V}} \times VA_{i,v}$$

[5]

where L represents labour (W its price), λ is the technical progress associated with labour, and KE is the capital-energy bundle (P^{KE} its price). The price of the value-added bundle, for generation ν, is:

$$P_{i,v}^{VA} = \frac{1}{A_{i,v}} \times \left[\alpha_{i,v}^{KE} \left(P_{i,v}^{KE}\right)^{1-\sigma_{i,v}^{V}} + \alpha_{i,v}^{L} \left(\frac{W_i}{\lambda_i}\right)^{1-\sigma_{i,v}^{V}} \right]^{(1/(1-\sigma_{i,v}^{V}))}$$

[6]

The value-added bundle (VA) is a sub-component of the top level node that produces sectoral net-of-GHGs output X_i. Similar sub-components also exist in formulating the capital and energy bundles. In fact, as shown in Figure 1, the capital is bundled with a sector-specific resource when one exists and energy is itself a bundle of different energy inputs.

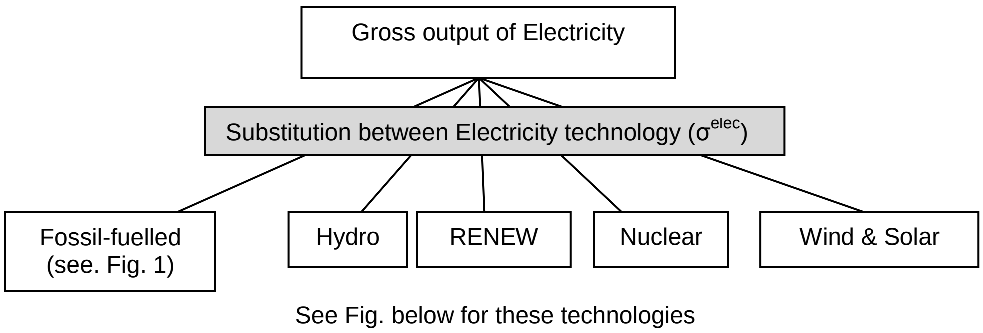
The structure of electricity production assumes that a representative electricity producer maximizes its profit by using the five available technologies to generate electricity using a CES specification with a large value of the elasticity of substitution (Figure 2). The production of the non-fossil electricity technology (net of GHG and expressed in TeraWatt per hour) has a structure similar than for the other sectors, except a top nesting combining a sector-specific natural resource, on one hand, and all other inputs, on the other hands. This specification aims at controlling the supply of these electricity technologies given the value of the substitution elasticity.

The energy bundle is of particular interest for analysis of climate change issues. Energy, as reported in Figure 3, is a composite of fossil fuels and electricity. In turn, fossil fuel is a composite of coal and a bundle of the “other fossil fuels”. At the lowest nest, the composite “other fossil fuels” commodity consists of crude oil, refined oil products and natural gas. The value of the substitution elasticities are chosen as to imply a higher degree of substitution among the other fuels than with electricity and coal.

Given the dual streams of production (from old and new capital), there is a higher degree of substitutability between energy sources when capital is new, but after one year it becomes a sunk cost and falls to a low level of substitutability among energy sources. Moreover, in the sectors that produce fossil fuels (with the exception of natural gas), there is no substitutability between energy inputs. The low level of substitutability of energy when old capital is present is consistent with empirical findings by Arnberg and Bjorner (2007) who look at plant level changes in energy intensity. However, since this model includes the possibility of changes in industry composition, the overall responsiveness to energy price changes will be higher than these researchers found at plant levels.

Total output for a sector is the sum of two different production streams: resulting from the distinction between production with an “old” capital vintage, and production with a “new” capital vintage. The substitution possibilities among factors are assumed to be higher with new capital than with old capital. In other words, technologies have putty/semi-putty specifications. This will imply longer adjustment of quantities to prices changes. Capital accumulation is modelled as in traditional Solow/Swan neo-classical growth model.

Figure 2. Structure of electricity generation



Structure of production of non-fossil technologies

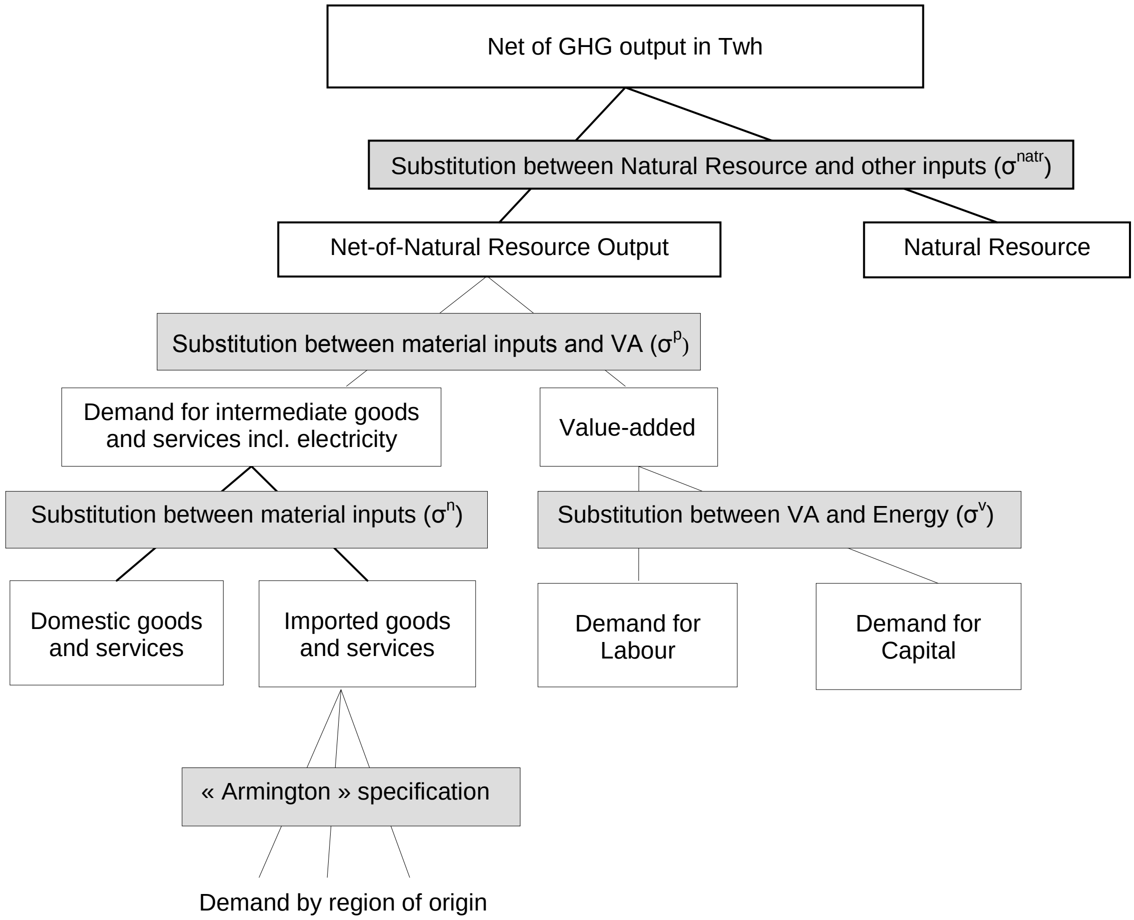
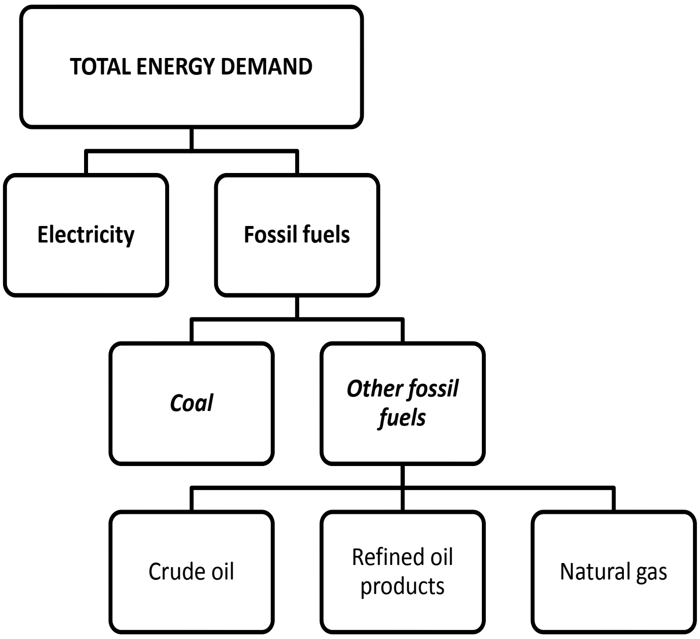


Figure 3. Structure of energy intermediate demands



Consumption

Household consumption demand is the result of static maximization behaviour which is formally implemented as an "Extended Linear Expenditure System". A representative consumer in each region – who takes prices as given – optimally allocates disposal income among the full set of consumption commodities and savings. Saving is considered as a standard good and therefore does not rely on a forward-looking behaviour by the consumer. Formally, a representative consumer maximises well-being (utility) subject to resource constraints:

$$Max \;\; U = \sum_k \mu_k \ln(C_k - \theta_k) + \mu_s \ln(\frac{S}{P_s})$$

$$Subject \; to \quad \sum_k P_k^c \; C_k + S = Y, \quad and \quad \sum_k \mu_k + \mu_s = 1$$

where U represents utility, C is a vector of k consumer goods, P^c is the vector of consumer prices, S represents the value of saving, P_s the relevant price of saving, and Y is total net-of-taxes income (completely allocated between consumption and savings). The parameter θ is the floor level of consumption – its main function is in making the utility function non-homothetic, which is consistent with considerable empirical evidence (*e.g.* Dowrick, *et al*. 2003). Since consumers are not represented with forward-looking behavior, some care needs to be exercised in studying policies that consumers may reasonably be expected to anticipate – either the policy itself or its consequences. For each country, the consumer's objective function thus gives rise to household private consumptions [7] and saving [8]:

$$C_k = Pop \times \theta_k + \frac{\mu_k}{P_k^c} \times Y^*, \quad where \;\; Y^* = Y^c - Pop \times \sum_k P_k^c \times \theta_k$$

[7]

$$S = Y^c - \sum_k P_k^c \times C_k$$

[8]

where *Pop* represents population, Y^c represents household disposable income and Y^* is a *supernumerary* income (i.e. income above the subsistence level).

Foreign Trade

World trade is based on a set of regional bilateral flows. The basic assumption is that imports originating from different regions are imperfect substitutes Therefore in each region, total import demand for each good is allocated across trading partners according to the relationship between their export prices. This specification of imports - commonly referred to as the Armington specification - formally implies that each region faces a reduction in demand for its exports if domestic prices increase. The Armington specification is implemented using two CES nests. At the top nest, domestic agents choose the optimal combination of the domestic good and an aggregate import good[9]. At the second nest, agents optimally allocate demand for the aggregate import good [11] across the range of trading partners *r'*.

$$XMT_i = \beta_i^m \times \left(\frac{PA_i}{PMT_i} \right)^{\sigma_i^m} \times XA_i$$

[9]

$$PMT_i = \left[\sum_r \beta_{i,r}^W PM_{i,r}^{\;1-\sigma_{i,r}^w} \right]^{(1/(1-\sigma_i^w))}$$

[10]

where X*MT* is the bundle of imports of a particular good or service (*PMT* its price) and *XA* represents the aggregate demand for domestically produced and import goods (*PA* is its price).

$$WTF_{r',i} = \beta_{r',i}^w \times \left(\frac{PMT_i}{PM_{r',i}^M} \right)^{\sigma_i^w} \times XMT_i$$

[11]

where $WTF_{r'}$ is import of a particular good or service from region *r'*. Its price, $PM_{r'}$, represents the domestic import price (*e.g.* domestic producer price of its partner r' adjusted for export tax or subsidy, transport margin, "iceberg" costs, and domestic tariffs).

Investment and Market goods equilibria

This version of the model does not include an investment schedule that relates investment to interest rates. In each period, investment net-of-economic depreciation is equal to the sum of government savings, consumer savings and net capital flows from abroad. Investment as well as government demand use final goods according with a CES specification. Then, the total demand of a good in the economy is equal to the consumer final demand plus the intermediary demands from firms plus the intermediary demands by final good sectors, corresponding to government and investment expenditures.

Market goods equilibria imply that, on the one side, the total production of any good or service is equal to the demand addressed to domestic producers plus exports; and, on the other side, the total demand is allocated, according to the Armington principle, between the demands (both final and intermediary) addressed to domestic producers and the import demand(see below).

Government and long-term closure

Government collects income taxes, indirect taxes on intermediate and final consumption as well as possible carbon taxes, production taxes, tariffs, and export taxes/subsidies. Aggregate government expenditures are linked to real GDP. Since predicting corrective government policy is not an easy task, the real government deficit is exogenous. The closure of the model implies that some fiscal instrument is endogenous – in order to meet government budget constraint. Given also a sequence of public savings (or deficits), the fiscal closure rule in ENV-Linkages is that the income tax rate adjusts to offset changes that may arise in government expenditures, or as a result of other taxes. For example, a reduction or elimination of tariff rates is compensated by an increase in household direct taxation, *ceteris paribus*. Alternative closure rules can be easily implemented.

For studying the impacts of climate change policy, four types of instruments have been developed: GHG taxes, global or specific by sectors, gases or emission sources; tradable emission permits (with flexibility between regions and sectors); offsets (including the Clean Development Mechanism) and regulatory policy (modelled as quantity constraints). Taxes and tradable permits are applied on inputs of fossil-fuel producing sectors (refined petroleum, natural gas, coal). They are applied, as well, on final demands of fossil-based energy. Regulatory policy has also been introduced in the model through a mechanism imposing a shadow cost on the firm's inputs or capital. It has the effect of changing the marginal cost of particular inputs, or changing the quantity of capital used to produce a given output, but does use market instruments. The analysis requires assumptions concerning the cost of the regulatory policy, but it breaks the link between policy instruments and revenue transfer that is inherent in tax policy and tradable permits.

Factor-income taxes as well as factor taxes and subsidies on factor supply have also been introduced as these instruments are distinguished in the GTAP version 6.2 database. From IEA databases we have also introduced fossil-fuel subsidies to energy demands.

Each region runs a current-account surplus (or deficit), which is fixed (in terms of the model *numéraire*). Closure on the international side of each economy is achieved by having, as a counterpart of these imbalances, a net outflow (or inflow) of capital, which is subtracted from (added to) the domestic flow of saving. These net capital flows are exogenous. In each period, the model equates investment to saving (which is equal to the sum of saving by households, the net budget position of the government and foreign capital flows). Hence, given exogenous sequences for government and foreign savings, this implies that investment is ultimately driven by household savings.

ENV-Linkages is fully homogeneous in prices and only relative prices matter. All prices are expressed relatively to the numéraire of the price system that is arbitrarily chosen as the index of OECD manufacturing exports prices. From the point of view of the model specification, this has an impact on the evaluation of international investment flows. They are evaluated with respect to the price of the numéraire good. Therefore, one way to interpret the foreign investment flows is as the quantity of foreign saving which will buy the average bundle of OECD manufacturing exports.

Dynamic Features

The ENV-Linkages model has a simple recursive dynamic structure as agents are assumed to be myopic and to base their decisions on static expectations concerning prices and quantities. Dynamics in the model originate from two endogenous sources: *i)* accumulation of productive capital and *ii)* the putty/semi-putty specification of technology, as well as, from exogenous drivers like population growth or productivity changes.

At an aggregate level, the basic capital accumulation function equates the current capital stock to the depreciated stock inherited from the previous period plus investment. Differences in sectoral rates of return determine the allocation of investment across sectors. The model features two vintages of capital, but investment adds only to new capital. Sectors with higher investment, therefore, are more able to adapt to changes than are sectors with low levels of investment. Indeed, declining sectors whose old capital is less productive begin to sell capital to other firms (which they can use after incurring some adjustment costs). [10]

The substitution possibilities among production factors are assumed to be higher with the *new* than with the *old* capital vintages — technology has a putty/semi-putty specification. Hence, when a shock to relative prices occurs (*e.g.* tariff removal), the demands for production factors adjust gradually to the long-run equilibrium because the substitution effects are delayed over time. The adjustment path depends on the values of the short-run elasticities of substitution and the replacement rate of capital. As the latter determines the pace at which new vintages are installed, the larger is the volume of new investment, the greater the possibility to achieve the long-run total amount of substitution among production factors.

2. Calibration of the ENV-Linkages model

The process of calibration of the ENV-Linkages model is broken down into three stages. First, a number of parameters are calibrated, given some elasticity values, on base-year (2001) values of variables. This process is referred to as the static calibration. Second, the 2001 database is updated to 2005 by simulating the model dynamically over the period 2001-2005 and static calibration is performed again with price re-normalisation in order to express all variables in 2005 real $US. Third, the baseline projection is obtained by defining a set of exogenous socio-economic drivers (demographic trends, labour productivity, future trends in energy prices and energy efficiency gains) and running the model dynamically again over the period 2005-2050.[11]

Static calibration of the model

Many key parameters are set on the basis of information drawn from various empirical studies and data sources (elasticities of substitution, income elasticities of demand, supply elasticities of natural resources, etc). Table 3 reports some key elasticities used in the current version of the model. Use of these parameters was illustrated in Figures 1 and 2, as well as by the equations in Section 3. Income elasticities of household demand as well as Armington elasticities are taken from the GTAP 6.2 database.

However, the information available on the values of these parameters is insufficient for the model simulation to be able to reproduce base-year data values. Given the modelling choices made with regard to the representation of both behaviours and structural technical relationships, some model parameters must be calculated to fit to the data for the initial year (expressed in 2001 $US) of the version 6 of the GTAP database. As a general rule, the parameters used to do this are those whose impact on the outcomes in terms of variation rates remains limited (scale parameters) or parameters for which there are no empirical studies (CES share coefficients). [12]

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[10] Formally, at the sectoral level, the specific accumulation functions may differ because the demand for (old and new) capital can be less than the depreciated stock of old capital. In this case, the sector contracts over time by releasing old capital goods. Consequently, in each period, the new capital vintage available to expanding industries is equal to the sum of disinvested capital in contracting industries plus total saving generated by the economy.

[11] The baseline simulation also contains the assumption that the EU Emission Trading System is implemented over the period 2006-2012, assuming a permits price that will rise gradually from 5 to 25 constant $US in 2012 and for the years after.

Table 5. Table 3. Key parameter values

Key parameter		Value
σ^{Ghg}	Substitution between GHGs bundle and Net-of-GHGs Output	Substitution is from 0.03-0.05 for Agr. Sectors to 0.15-0.3 in some industrial emissions
σ^{p}	Substitution between material inputs and VA plus energy	Substitution between material inputs and VA plus energy is 0, except for new capital in manufacturing where it is 0.1.
σ^{n}	Substitution between material inputs	Substitution between material inputs is 0 for non services and non manufacturing sector and 0.1 for other sectors.
σ^{V}	Substitution between VA and Energy	0.05 for old capital vintages and 0.4 for new vintages in agriculture, forestry and fishing and fossil fuels sectors and varying form 0.2-0.27 (1.8-2.1 in other sectors)
σ^{f}	Substitution between inputs investment and government exp.	0.8
σ^{E}	Substitution between Capital and Energy	0 for old capital vintages, 0.2-0.8 for new vintages, but always 0 in coal and crude oil.
σ^{k}	Substitution between Capital and Specific Factor	Substitution between Capital and Specific Factor is 0
σ^{ELY}	Elasticity between Electricity & Non-electricity energy inputs	0.062 for old capital and 0.5 for new in electricity sector. 0.12 and 1 in other sector except fossil fuel where equals to 0 and chemicals where 0.08 and 0.4.
σ^{Coa}	Elasticity between Coal & Non-Coal bundle	0.03 for old capital and 0.25 for new in electricity sector. 0.12 and 1 in other sector except fossil fuel where equals to 0.
σ^{Ep}	Elasticity between enery inputs in Non-Coal bundle	0.25 for old capital vintages, 2 for new vintages, but always 0 in the energy sectors, except for Electricity
σ^{X}	Armington elasticity, domestic versus imports	Varies from 0.9 to 5depending on sectors, identical across regions. GTAP data is used
σ^{W}	Armington elasticity, import sources	Same as σ^{X}
σ^{M}	Armington elasticity, intermediate goods imports	Same as σ^{X}
σ^{EI}	*Armington elasticity, energy imports*	*Same as* σ^{X}
σ^{elec}	Elasticity between electricity technologies	10
σ^{natr}	Elasticity between specific resource and other inputs	Only for non-fossil electricity technologies, varying form 0.0-0.4

Dynamic calibration of the model

Ideally, an informed choice of prospective trends in exogenous variables would produce a set of acceptable scenarios. However, it is difficult to cover all these trends comprehensively. Furthermore, this would make comparisons of different alternative scenarios practically unmanageable. Therefore, the approach followed here considers only one single set of exogenous drivers while recognising that alternative sets may potentially generate somewhat different simulation results. The baseline projection allows calculating the values of a number of parameter over time (such as energy efficiency gains, for instance), in order to reproduce the evolution of the exogenous drivers. In any variants or policy simulations, these parameter values are kept constant while all other variables in the model are fully endogenous.[13]

The list of exogenous drivers specified in the baseline projection is the following:

- Demographic projections and employment trends,
- Aggregate average and sectoral labour productivity growth, controlled by calibration of technical progress coefficients embodied in labour,
- Autonomous efficiency gains for capital, land and specific natural resources,
- Autonomous efficiency gains of fertilizers in crops sectors and of the food bundle in livestock rearing,
- Supply of land and natural resources (excepted for fossil fuels sectors),
- International trade margins,
- Shares of public expenditure in real GDP,
- Public savings and flows of international savings,
- Energy demands (projected by using elasticities of demands to GDP), for all kind of fuels demands excepted crude oil, controlled by calibration of the Autonomous Energy Efficiency Improvements (named AEEIs) in energy use, by sector and type of fuel,
- International prices of fossil fuels, controlled by calibration of the potential supply of fossil fuels resources,
- Investment to GDP ratios, controlled by calibration of the marginal propensity to save of the households,
- Non-CO_2 fuel GHGs emissions, controlled by calibration of autonomous efficiency gains in non-CO_2 GHGs emissions, by sector and type of GHGs emissions,
- The share of each type of electricity-producing technology, controlled by calibration of the specific “natural resource”.

Note on data sources

Socio-economic variables such as population, apparent labour productivity or investment to GDP ratios are discussed the Annex 2. Sectoral labour productivity growth rates used to calibrated the model are extracted from OECD-STAN database as well as Groningen Database for non-OECD countries.

AEEIs in energy uses have been dynamically calibrated on the basis of elasticities of each kind of energy demand to GDP for 2005-2030 as projected in the IEA’s *World Energy Outlook* (2006-2008). These elasticities are assumed to evolve after 2030 in line with their projected trends over the period 2025-2030.The structure of electricity production between the five alternative technologies is calibrated based on the projections from the IEA’s *World Energy Outlook* (2008). The evolution of the international import prices of fossil fuels are also controlled for in the baseline scenario. During the period 2005-2008, the model reproduces the historical evolutions and short run projections made by the IEA for its *World Energy Outlook 2008* report.

The non-CO_2 greenhouse gases need to be calibrated in the base year database. For this purpose, the price of these emissions is arbitrary set equal to 0.5 USD per ton of CO_2 equivalent in the upper bundle of the gross output. Emissions by source reported in US EPA (2006b) are associated to the sectors of ENV-linkages, and for sake of consistency GHGs levels in 2005 are adjusted to match IEA data in this study. It

[13] For instance, in the baseline scenario, the technical progress embodied in labour is calibrated to reproduce given GDP trends. In contrast, in any policy variants, GDP is fully endogenous given this technical progress calculated in the baseline scenario.

was not possible to associate all emission sources to an economic activity described in the model.[14] For the period 2005-2020, the non-CO_2 emissions are calibrated on forecasts made by the US EPA by adjusting an autonomous efficiency parameter in the emissions bundle of the production function. After 2020 the trend over the period 2015-2020 is extended, except for agriculture sources of non-CO_2 GHGs emissions where the trend assumed is taken from the OECD Environmental Outlook (2008).

A carbon dioxide emissions database has been developed for GTAP (Lee, 2002) that uses data provided to GTAP by the International Energy Agency. The emission rates for non-CO_2 gases come from US-EPA (2006a). 27 sources of emissions over the 32 censed by US-EPA are implemented in the model.

From 2001-2005, current account balances as well as government savings are calibrated to match OECD-IMF historical data. After 2005, government deficits (or surplus) as well as current accounts deficits (or surplus) are assumed to gradually vanished (at an arbitrary 2.5% rate of reduction per year). However, the Chinese surplus and US deficit are assumed to disappear less rapidly (only after 2020).

Structural dynamic changes

In addition, the parameters relative to household demands (see equations 1-3) need to be recalibrated dynamically in the baseline simulation. The household preferences in ENV-Linkages include a minimum subsistence level of demand for each good that makes the utility function non-homothetic. However, when using the model over a rather long projection horizon, household income increase quite substantially and, if the minimum subsistence demands are not adjusted, income elasticity of demand for all goods converge towards unity. This problem is offset by adjusting the subsistence parameters in the baseline scenario for each period in order to reproduce the desired set of income elasticities. Moreover in the baseline simulation, income elasticities of demand are evolving over time assuming, a conditional convergence of household preferences (*e.g.* income elasticities of demand for non-energy goods) of the non-OECD countries to the OECD standard, based on relative income per capita.

In a model like ENV-Linkages that uses so-called Armington specifications to represent international trade flows, countries face downward sloping demand for their exports. Therefore, a fast-growing country would typically experience a decline in its relative factor prices, implying a depreciation of its real exchange rate, *ceteris paribus* (abstracting from the offsetting Balassa-Samuelson effect). This appears inconsistent with past history, which shows that imports from fast-growing countries have typically increased through the creation of new products rather than through price reductions (see in particular Krugman, 1989). In order to capture this historical feature in a simplified manner, the baseline projection further assumes a gradual exogenous increase in the share of non-OECD countries in the overall imports of OECD countries.

In addition, the increase in global competition is accompanied by growth in the use of services in production, in line with the argument advanced in OECD (2005). This is simulated by adjusting dynamically the input-output structure such as to increase the weight of services (in the broad sense of the term) in the composition of the bundle of intermediate goods, for non-agricultural and non-fossil fuels sectors.

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14. Non-CO_2 emissions from forest and savannas' burning are not introduced. They correspond to less than 5% of the non-CO_2 emissions reported by the US EPA.