CARBON EMISSION LEAKAGES: A GENERAL EQUILIBRIUM VIEW

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ABSTRACT/RÉSUMÉ

In December 1997, a number of countries - referred to as the Annex 1 countries - signed the Kyoto Protocol under which they agreed to ceilings on their emissions of greenhouse gases (GHGs). Such unilateral action by a group of countries has often been criticised on the grounds that it could be undermined by the existence of so-called “carbon leakages”. Carbon leakage refers to the possible rise of GHG emissions in countries that do not participate in a carbon abatement coalition. This paper provides a discussion of the key mechanisms and factors underlying the size of carbon leakages. To this aim, we use a two-region, two-final goods simplified CGE framework, incorporating three types of fossil fuels (coal, oil and low-carbon energy), international trade and capital mobility. This framework was designed to make extensive, multidimensional sensitivity analysis tractable. Indeed, a wide range of alternative assumptions and parameterisations would have been difficult or even impossible to simulate and interpret with a large general equilibrium (GE) model. Amongst different determinants of carbon leakages, the results suggest that the supply elasticity of coal plays a critical role. The degree of product differentiation of manufactured goods and the international capital mobility appear as relatively less influential. The shape of the production function also matters, a fact that has attracted little attention so far. Our analysis also suggests that the level of leakage rates is low within the range of parameters provided in the literature and corresponding to the ones embodied, for example, in the OECD GREEN model.

JEL classification: D58, Q32, Q43.

Keywords: Computable and other Applied General Equilibrium Models, Exhaustible Resources and Economic Development, Energy and the Macroeconomy.

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En Décembre 1997, les pays dits “de l’Annexe 1” signaient le Protocole de Kyoto par lequel ils s’engageaient à limiter leurs émissions de gaz à effet de serre (GES). On a souvent mis en doute l’efficacité de ce type d’action unilatérale par un groupe de pays à cause de l’existence possible de ce que l’on peut appeler des « fuites de carbone ». Ces fuites correspondent à l’augmentation induite éventuelle des émissions de GES dans les pays qui ne participent pas à la coalition engagée dans l’effort de réduction des émissions. On trouvera dans ce document une discussion des facteurs et des mécanismes qui déterminent la taille des « fuites de carbone ». Cette analyse utilise un modèle d’Équilibre Général Appliqué (EGA) simplifié comprenant deux régions, deux biens de consommation, trois types d’énergie fossile (charbon, pétrole et une énergie à faible contenu en carbone), du commerce international et de la mobilité interrégionale du capital. Il s’agit avec ce type de modèle de pouvoir réaliser une analyse de sensibilité multidimensionnelle la plus complète possible. Il aurait en effet été très difficile, voire impossible, de simuler et d’interpréter toutes les hypothèses alternatives relatives aux paramètres en utilisant un modèle EGA complètement spécifié. Les résultats indiquent que l’élasticité d’offre du charbon joue un rôle prépondérant dans la détermination de la taille des « fuites de carbone ». Par contre, le degré de différenciation des biens manufacturés ainsi que le degré de mobilité internationale du capital semblent avoir une influence moindre. La forme de la fonction de production est importante également. Enfin, l’analyse suggère que les « fuites de carbone » devraient être relativement faibles pour les ordres de grandeur des paramètres que l’on trouve dans la littérature et qui ont été utilisés, par exemple, dans le modèle GREEN de l’OCDE.

Classification JEL : D58, Q32, Q43.
Mots-Clés : Modèles d’Equilibre Général Appliqués et Calculable, Ressources non renouvelables et Développement Économique, Énergie et Macro-économie.

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CARBON EMISSION LEAKAGES: A GENERAL EQUILIBRIUM VIEW

Jean-Marc Burniaux and Joaquim Oliveira Martins

1. Introduction

1. Against the background of increasing scientific consensus about the influence of manmade emissions of greenhouse gases (GHGs) on Earth climate, a number of industrialised countries signed the Kyoto Protocol in December 1997 committing these countries to reduce their emissions of the main GHGs. Beside uncertainties about the practical implementation of this treaty, such unilateral action by a group of countries (so-called Annex 1 countries) has raised serious concerns about its environmental effectiveness. Firstly, the impact of the Protocol on world emissions is likely to be very modest. Secondly, this already small impact could be further reduced if emissions in countries that have not signed the Protocol increase as a result of the mitigation effort undertaken by the Annex 1 countries. In the literature on climate change policy, the latter effect has been referred to as “carbon leakages”. The possibility of large carbon leakages would cast serious doubt on the effectiveness of an unilateral strategy - like the one decided in Kyoto - to reduce the speed of climate change. It also would make the extension of the Protocol to non-Annex 1 countries rather problematic as large leakages reinforce the free-riding incentives for non-participating countries.

2. Therefore, assessing the potential for carbon leakage is a central piece in the evaluation of the Kyoto Protocol and its chances of being extended world-wide. But this is not an easy task. Indeed, the leakage effects are the result of complex interactions between energy and non-energy markets. In the absence of any direct empirical evidence, an option is to rely on model simulations. However, existing global models have failed so far to provide a coherent view on the magnitude and the regional distribution of the carbon leakages that could emerge following the implementation of the Protocol. This paper contributes filling this gap by discussing the main determinants of leakages and quantifying their magnitude.

3. Table 1 provides evidence on the divergence of leakage rate estimates based on various existing models. The “leakage rate” is defined here as the ratio of the additional emissions in the non-Annex 1 countries to the emission reduction achieved in Annex 1 countries. The estimates range from around 20

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2. Referred to as Annex 1 countries in the discussion even though the Protocol lists them in annex B.
3. According to projections from the OECD Secretariat GREEN model, implementation of the Kyoto Protocol would reduce world emissions by 9 per cent in 2010 compared to a business-as-usual scenario (see also OECD, 1999).
4. The literature based on game theory shows that higher leakage rates reduces the size of a stable, self-enforcing coalition to reduce emissions (see, for instance, Carraro, 1998; Botteon and Carraro, 1998).
per cent in WorldScan, MERGE and Rutherford’s models to the lower bound estimates of 2 to 5 per cent provided by the GREEN, G-cubed and EPPA-MIT models.

4. So far, the literature has shed light on the factors underlying these divergences. Using the OECD GREEN model, Oliveira Martins (1996) presented sensitivity analysis showing that the values of the energy supply elasticities appear more influential in determining leakage rates than the elasticity of substitution in the world markets for energy-intensive goods. The analysis also points to the possibility of negative leakage effects, i.e. a possible reduction of emissions in some non-participating countries. This effect is due to the fall of the international relative price of oil vis-à-vis coal, which induces a shift towards less carbon-intensive energy consumption in the non-participating countries. These negative leakages explain part of the low net leakage rate in a model like GREEN. Also using a sensitivity analysis approach, Bollen et al. (1999) show that an important factor determining the magnitude of carbon leakages are the substitution possibilities in the production function. Finally, Light et al. (1999) assert that the structure of the international coal market is critical to understand the leakage mechanisms; if the degree of integration of the coal market is understated this necessarily leads to underestimation of the carbon leakages. The analysis developed below will show that this result actually holds only for a restricted and low range of values for the supply elasticity of coal. In other words, even when coal is treated as an homogenous commodity, assuming a relatively elastic supply of coal still leads to low leakage rates.

5. Drawing robust conclusions in this area is made difficult by the need to take into account the interactions between different parameters over a wide range of values. Overlooking this multidimensionality aspect can lead to false, or at least incomplete, interpretation of the factors and the mechanisms underlying carbon leakages. Figures 1a and 1b illustrate this point. We assumed hypothetically the leakage rates as a continuous function of two given parameters, a and b. In Figure 1a, we depicted an extreme case where the sensitivity with respect to parameter a does not depend on parameter b. Therefore, a unidimensional sensitivity analysis is legitimate. But in the case portrayed in Figure 1b this does not apply anymore. Indeed, the sensitivity of the leakage rate with respect to parameter a is conditioned on the value of parameter b. In other words, in the latter case a multidimensional sensitivity analysis is required.

6. However, multidimensional sensitivity analysis is also subject to limitations. Notably, analysing the interactions amongst three or more parameters simultaneously is in practice difficult and not easy to interpret. Moreover, the number of simulations required to perform a sensitivity analysis over a wide range of parameter values becomes rapidly very large. This reduces the tractability of multidimensional sensitivity analysis with a large-scale general equilibrium (GE) model. In order to circumvent this problem, in this paper we use a simplified GE framework, described below. We also restrain our analysis to only two-dimensional interactions. The model simulations were carried out iteratively over a grid of parameters’ values. This makes it possible to draw in a three-dimensional space the manifold representing the leakage rate as a function of each pair of parameters. Important to note, this simplified framework was calibrated on the basis of the dataset of the GREEN, and its results were validated, as well, by tests ran with the full-blown model.

2. The key mechanisms underlying carbon leakages

7. Carbon leakages can be generated through different mechanisms. To simplify, two main general equilibrium channels can be distinguished: energy and non-energy markets.

5. The paper by Light et al. (1999) quoted in Table 1 is based on a model developed by Thomas Rutherford (University of Colorado, Boulder).
8. In the channel that operates via non-energy markets, carbon abatement imposed unilaterally raises production costs affecting the competitiveness of energy-intensive industries. These industries can lose market shares in the international markets in favour of industries located in countries that do not reduce their emissions; this causes a corresponding shift in the production of energy-intensive goods at the world level. The trade substitution elasticities (the so-called Armington elasticities) usually represent the intensity by which this mechanism operates. The larger these elasticities, the larger the effect of prices on market shares. In addition to the direct effects in goods markets, unilateral carbon constraints can also induce a reallocation of foreign direct investments to non-participating countries. This also contributes to the carbon leakages occurring through the non-energy channel and the key parameter here is the degree of international mobility of capital.

9. The channel related to energy markets operates in the following way. When a unilateral carbon abatement occurs in a large country group, the reduction in world demand would cause a fall of the international price of the most carbon-intensive fossil fuels, thus increasing energy demand and carbon emissions in the non-participating countries. But, the structure of the international energy markets matters for the size and scope of this effect.

10. Indeed, while oil can be considered a fairly homogenous good there is more uncertainty about the degree of integration of the world coal market. There are many coal varieties and secondary energy producers may not shift easily from one to another source of supply. Perhaps even more important than the structure of the international carbon market, the supply response of fossil-fuel producers will also be determinant. Indeed, the potential for reducing world carbon emissions ultimately relies on the decision by the carbon producers to keep extracting carbon-based energy or to leave it in the ground. The key parameters characterising the behaviour of carbon producers are the supply elasticities for coal, oil and natural gas. Given that coal is the most carbon-intensive fuel, the supply elasticity of coal can be expected to be influential for the size of carbon leakages.

11. There are a number of other factors that may also prove important. Firstly, in the specific context of the Kyoto Protocol, the existence of so-called “hot air” in the Russian Federation and Ukraine implies that emissions in these two countries are not subject to any binding constraint. This raises the possibility of carbon leakages within the group of the Annex 1 countries. Secondly, after the implementation of the Kyoto Protocol, a fall of the international price of oil relative to the coal price would lead to a shift of energy demand from coal to oil. This would induce a fall of the carbon intensity in some large coal consuming countries, like China (inducing the “negative leakages” referred above). These negative leakages are most likely to appear if the supply elasticity of oil is small while the supply of coal is elastic. Finally, the size of the leakages can also depend on the loss of income in energy-exporting economies, reducing their domestic demand and carbon emissions (hence also creating negative leakages). But this factor is likely to be of a second order influence over the time horizon of the first budget period of the Protocol.

3. A simplified General Equilibrium framework

12. This section describes a two-country, multi-good, simplified general equilibrium framework designed to make more tractable an extensive sensitivity analysis. The model captures in a stylised way the

6. High transportation costs, lack of infrastructure and other technical aspects have so far contributed to restrict coal trading to a fraction of the world coal production, although Light, Light and Rutherford (1999) argue that the international coal market is actually more integrated than it appears.

7. The analysis of Light et al. (1999) is based on the assumption of a very inelastic coal supply (with a supply elasticity equal to 0.5). This assumption alone leads them to rule out the possibility of negative leakages.
The main interactions described above between energy and non-energy supplies and demands. The two regions correspond to the group of countries that have signed the Kyoto Protocol (referred to as Annex 1 countries) and the rest of the world group (non-Annex 1 countries). Each region uses five inputs: a region-specific labour and fixed factor, capital, and three energy inputs: coal, oil and a residual low-carbon energy source which groups natural gas and other, carbon-free energy sources. Both regions produce the three energy sources. Coal and oil are tradable commodities with coal being differentiated by origin (Armington specification) and oil being treated as a homogenous commodity. The carbon-free energy source is considered as a region-specific, non-tradable good. The final good produced in each region is differentiated by region of origin. Moreover, it was important to consider the international mobility of capital because this may be a possible channel for carbon leakages, as discussed above. The complete production nesting is depicted in Figure 2.

The model specification is based on a linear approximation of nested-CES functions and log-linear supply functions of fossil fuels. The capital mobility was modelled through a Constant Elasticity of Transformation (CET) function, with the transformation elasticity characterising the degree of international mobility (zero for immobile capital and one for perfect mobility). For further details, the list of variables and equations is provided in the Annex. The model was calibrated on actual 1995 data taken from the GREEN database. It is solved iteratively for different pairs of parameter values. In this way, becomes possible to represent graphically the sensitivity of the leakage rate over a wide range of parameter values.

Table 2 reports the values of the key parameters corresponding to the current specification of GREEN (referred to as the central case), also used in the simplified model used here. Most of these parameter values are in the range of those reported in the literature (see Burniaux et al., 1992a-b). In this specification, oil is treated as an homogenous commodity while the international coal market is characterised by a rather moderate degree of differentiation (with a trade substitution elasticity equal to 5). In contrast, coal is available with a highly elastic supply (the supply elasticity is equal to 20) compared with the supply of the other energy sources (characterised by unitary supply elasticities). In the absence of more detailed evidence (see below), the presumption is that large profits in oil and gas extraction and electricity production correspond to some market power in these sectors (hence a low supply elasticity). This does not seem to be the case in the coal mining industry.

Based on this set of parameters, we simulated the implementation of the Kyoto Protocol assuming full usage of the “flexibility mechanisms” among Annex 1 countries. The simplified model replicated a leakage rate comparable to the one obtained with GREEN (see Table 1) of around 2 per cent.

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8. This aspect has been overlooked in previous studies, significant exception being the G-Cubed model (McKibbin and Wilcoxen, 1995).
9. Based on a usual linearisation procedure of CES functions, see for example Dixon et al. (1992).
10. The latest version of GREEN is based on the GTAP-E data base for 1995 (see Hertel, 1997). The non-traded factors are the equivalent of the labour, land and natural resources fixed-factors in GREEN.
11. In principle, it should be possible to compute algebraically the exact functional form of the leakage rate as a function of the key parameters. However, even this simple model turned out to be too complicated to be solved algebraically. The calculations were carried out with Mathematica (see Wolfram, 1991). Further details can be supplied upon request.
12. This meaning that the Annex 1 group has an aggregate target of carbon emission reductions.
4. Sensitivity analysis

16. This section reports on simulations to assess how leakage rates react to changes in assumptions concerning parameter values. In line with the above discussion, the analysis considers parameters affecting the responses in energy and non-energy markets as well as those affecting changes in the input mix of production.

4.1 Non-energy markets

17. Figure 3 shows the joint sensitivity of the leakage rate to the elasticity of substitution between domestic and imported non-energy goods and the migration elasticity of capital. For the large range of parameter values explored in the chart, the leakage rate never exceeds a small 4 per cent (compared with 2 per cent in the central case). The leakage rate can even become negative when the trade elasticity is small and capital is fully mobile. The main result of this analysis is that the leakage rates remain small even with a high degree of product substitution in non-energy markets (including energy-intensive industries). This result suggests that the choice between the so-called Armington and Heckscher-Ohlin type assumptions is largely irrelevant for explaining the differences in leakage rates across models.

18. Contrary to some a priori views, capital mobility has only a small impact on the leakage rate and its effect is conditioned by the value of the trade elasticities. The mechanisms are as follows. For moderate values of the Armington elasticity (e.g. the range used in GREEN), the unilateral abatement in Annex 1 countries induces lower energy imports and a fall in world energy prices. This induces a current account surplus and a resulting real exchange rate appreciation, implying a net inflow of capital from the rest of the World to the Annex 1 countries. In other words, the flow of capital goes in the opposite of the expected direction, or capital mobility does not contribute to carbon leakages. Actually, for very low values of the trade elasticity and a high degree of capital mobility, emissions fall in the Non-Annex 1 group creating a negative leakage. Only for high values of the Armington elasticities, there is a small deterioration in the real exchange rate of Annex 1 countries leading to the expected net flow of capital from the Annex 1 to the non-Annex 1 countries. In this case, the leakage rate increases slightly (Figure 3).

19. To sum-up, only an unrealistically high degree of substitution between non-energy products together with full capital mobility yields a shift of carbon emissions from Annex 1 to non-Annex 1 countries, but, even with this combination of parameters, the leakage effect is rather modest.

4.2 Energy markets

20. Concerning energy markets, the key parameters involved are the supply elasticity of carbon-intensive fuels and the degree of integration in the international coal market. While these two aspects are inter-related, they are treated separately in order to assess each individual impact on the leakage rate.

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13. Noteworthy, while the average leakage rate remains modest, the marginal leakage rates (or the incremental changes in the leakage rates) can be rather large. Important to note, an optimal carbon tax depends critically on the marginal leakage rate and not on its absolute level (see Oliveira Martins, 1996, footnote 11).

14. The standard Heckscher-Ohlin model of international trade assumes that goods from different origins are homogeneous (or, put differently, their consumption has an infinite elasticity of substitution).

15. Note that when products are differentiated by region, producers have some market power, i.e. they have to decrease their supply price in order to increase their market shares and vice-versa.
4.2.1 Role of the supply elasticities of carbon-intensive fuels

21. In Figure 4, the leakage rate is plotted as a function of the values of the supply elasticities of coal and oil.16 The results are intuitively appealing. When the supply of high-carbon fuels is totally inelastic (i.e. a zero supply elasticity), a reduction of carbon consumption in Annex 1 countries will lead to a fall in their world prices in order to maintain the same level of demand. In other words, it is impossible to reduce world emissions, as any unilateral abatement by one region will be automatically offset by an equivalent increase of emissions in the other region. In this case, as shown in Figure 4, the leakage rate will be equal to 100 per cent. For values of the coal supply elasticity higher than zero but lower than or equal to 2, the leakage rate reaches 20 per cent and above.

22. In comparison with the supply elasticity of coal, the supply elasticity of oil appears to play a relatively minor role. With an inelastic supply of oil, but an elastic supply of coal, the leakages are small. Alternatively, with coal supply being fully inelastic and the supply elasticity of oil increasing to infinity, the leakage rate would stabilise at around 50 per cent. Compared with oil, the degree of flexibility of the supply of the low-carbon energy is even less influential (Figure 5).

23. The bottom-line from these results is that the size of carbon leakages is sensitive to the reaction of coal producers at the world level. Under the assumption of an elastic supply of coal, as specified in the GREEN model, the leakage rates are small.

4.2.2 Influence of the degree of integration in the international coal market

24. Another potential channel for leakages is the degree of integration of the coal market (see Light et al., 1999). In our model, the coal produced in different regions is specified as a differentiated product. The trade substitution elasticity characterises the degree of integration in the international coal market: the higher this elasticity, the more integrated is the market. Figure 6 provides the joint sensitivity of the results with respect to this elasticity and to the supply elasticity of coal, which appeared as a key parameter in the tests described above. The results show that influence of the coal trade elasticity is strongly conditioned by the coal supply elasticity. When coal supply is elastic (e.g. with a supply elasticity higher than 4-5), coal prices are relatively stable and the degree of integration in the coal market does not play a crucial role; in this case the leakage rates are uniformly low.17 Following the carbon abatement in Annex 1 countries, the excess supply coal would be left in the ground. However, with a less elastic supply of coal, the influence of the trade elasticity becomes considerable. Indeed, when the supply is inelastic and the coal market well integrated, the carbon mitigation in Annex 1 countries induces a large shift of exports and coal consumption towards non-Annex 1 countries, therefore generating a high leakage rate (above 60 per cent in Figure 6).

25. However, for this effect to take place a massive shift of exports would be required. For example, according to simulations with the GREEN model (see OECD, 1999), the implementation of the Kyoto Protocol would cut by half the consumption of coal in most OECD countries. For the US economy, re-directing this excess supply to external markets would imply increasing coal exports to non-Annex 1 countries by a factor of 14! High transportation costs, the difficulty of building-up infrastructure over the relatively short period, before the first target period under the Kyoto Protocol, as well as the propensity of

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16. The values of the supply elasticities are set equal in Annex-1 and non-Annex 1 regions.

17. As noted above, even when it applies to extremely low levels, the marginal leakage rate can be rather large. For instance, with a supply elasticity of coal equal to 10, the leakage rate would more than double (from 3 to 5 per cent) when the trade elasticity increases from 0 to 100.
the major non-Annex 1 coal consumers (China and India) to protect their own domestic coal industry suggest that this outcome highly unrealistic.

4.3 The shape of the production function also matters

26. Considering the degree of technological flexibility in the production can further enrich the results obtained above. The shape of the production function can be represented in our framework by the substitution elasticities between the energy composite good and value added, on one hand, and between the three different energy sources, on the other hand (according to the production nesting depicted in Figure 2).

27. Figure 7a shows how the leakage rates depend on the value of the inter-fuel substitution elasticity. As in previous simulations, the shape of this function is conditioned by the values of the other parameters. Firstly, we explored the sensitivity with respect to the inter-fuel elasticity of substitution under three alternative values for the supply elasticities of oil and low-carbon energy. When the latter elasticities are equal to one (as in the central specification), the leakage rate displays a U-shaped form, with the turning point corresponding to an inter-fuel elasticity around 5. Below this threshold the leakage rate is a decreasing function of the inter-fuel substitution. Above that value the leakages increase monotonically to reach more than 20 per cent. The GREEN model embodies inter-fuel substitution elasticity equal to 2, thus it stands on the downward sloping segment of the curve. The level of the inter-fuel substitution elasticity contributes to the low leakage rates obtained with GREEN.

28. The U-shaped pattern reflects opposite influences of demand and substitution effects. With relatively low substitution elasticities, the demand effect dominates in Annex 1 countries (i.e. all fuel demands decrease). Given the central specification of the model, the price of oil falls more than the price of coal and there is a corresponding shift in the non-Annex 1 countries towards a less carbon-intensive fuel mix, which in turn depends on the inter-fuel substitution possibilities. In this context, increasing fuel substitution induces lower emissions in non-Annex 1 countries (or the marginal leakage rate is negative). This is reflected by the declining part of the U-shaped curve.

29. For high values of the inter-fuel substitution elasticity, the substitution effect dominates in Annex 1 countries: while the demand for coal is reduced drastically, the demand for oil and low-carbon energy increases substantially. As the latter are in limited supply, their world prices increase inducing a shift in the non-Annex 1 countries towards coal consumption and thereby inducing an increase of carbon emissions. In this case higher substitution possibilities are translated into increasing leakage rates.

30. Therefore the shape of the leakage function relative to the degree of inter-fuel substitution reflects the pattern of the supply elasticities of the various fuels and, in particular, the fact that the less-carbon intensive fuels are assumed to be in restricted supply. Assuming an elastic supply for oil eliminates the U shape and flattens the slope of the increasing segment (see Figure 7a). Assuming further that the supply of the low-carbon fuel is elastic flattens even more the leakage function, leading to leakage rates below 6-7 per cent.

31. Figure 7b shows the leakage rate as a function of the inter-factor substitution elasticity (i.e. between the energy bundle and value-added). The pattern of the results and underlying mechanisms are

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18. Given the major role played by the coal supply elasticity, it obvious that the results would be dominated by this parameter. We found it more interesting to explore whether the former results concerning the supply elasticities of oil and low-carbon energy are changed upon different assumptions on the shape of the production function.

19. Where the coal supply is more elastic than the one of oil.
similar to those of the previous figure. With the values of the supply elasticities assumed in the central case (corresponding to those of GREEN), increasing inter-factor substitution induces higher leakages. Here again, this higher leakage reflects the rigidity of the supply of oil and the less-carbon intensive fuel to adjust to demand.\(^{20}\) Indeed, assuming elastic supplies for these fuels drastically flattens the leakage function.

32. To sum-up, these results introduce some nuances to the main conclusion from previous sections. Indeed, even under the assumption of an elastic supply of coal, when the oil and other fuels are in restricted supply and the possibilities for inter-fuel and/or inter-factor substitution are greater than it is usually reported in the literature, then there is a potential for high leakage rates. The intuition behind this result is simple. The shifts in energy demand in non-Annex 1 countries are larger with higher substitution possibilities and will be fulfilled by the most abundant energy source, i.e. coal.\(^{21}\) But, for the elasticity values within the range reported in the literature,\(^{22}\) the leakage rate should remain moderate. Testing the joint sensitivity to the inter-fuel and inter-factor elasticities of substitution (Figure 8), provides an additional confirmation of that result. With high substitution elasticities (especially inter-factor substitution\(^{23}\)), the carbon leakages are large even under the central case specification for the other parameters. The region corresponding to the parameter values used in the GREEN model is marked in Figure 8. It can be seen that it corresponds to the lower corner of the function. This also explains why the leakage rates tend to be so small in the GREEN model.

5. Validation of the results with the GREEN model

33. As with the central case, we tested whether results obtained with the simplified model are consistent with those of the GREEN model. Table 3 reports the sensitivity analysis carried out with the GREEN model under some of the alternative parameter specifications described above. This test is rather conclusive. As with the simplified model, an inelastic supply of coal yields high leakage rates, which are sensitive to the degree of product substitution in the coal market (13 per cent leakages with a low degree of substitution; 23 per cent with high substitution). In contrast, the leakage rate is small and rather stable when the supply of coal is elastic, whatever the assumptions on the coal trade elasticities.

34. This validation test illustrates the usefulness of using a simplified model to guide sensitivity analysis. Once the key general equilibrium interactions and parameters are identified, then it is much easier to run simulations with the fully specified model. The approach followed in this paper could actually be applied to other models. In principle, it is always possible to extract the "core" of a large GE model, build a simplified version and use it to explore how the equilibria manifold depends on parameter values. Subsequently, this sensitivity analysis would have to be validated in the large model. In this way, the two modelling frameworks become complements rather than substitutes.

20. The mechanism is as follows. Higher substitution implies that, as a result of carbon mitigation, the demand for labour and capital increases strongly in the Annex 1 countries. As these factors are in fixed supply, their prices increase. This increase is passed on to non-Annex 1 markets through the non-energy channels. The additional demand in non-Annex 1 countries is met by using the factor in most elastic supply - i.e. coal - thus implying higher leakage. When the constraints on the supply of oil and the low-carbon fuel are relaxed this considerably reduces the scope for carbon leakages.

21. However, this may not hold in a dynamic framework, as the supply of capital and the low-carbon energy tend to become elastic over the longer term.


23. Note that, according to Figure 7b, a value of 2 of the inter-factor substitution elasticity would generate a leakage rate equal to almost 10 per cent (against 2 per cent with an elasticity value of 0.4).
6. Empirical evidence on the supply elasticity of coal

35. The analysis developed in this paper suggests that the value of the supply elasticity of coal is likely to be critical in determining the size of carbon leakages. Unfortunately, there is little evidence in the econometric literature concerning the value of this elasticity. For the last twenty years, coal production has been steadily increasing while the real price of coal has declined (see Figure 9). A simple regression based on such a correlation would generate a negative supply elasticity. This would not be consistent with the microeconomic foundation underlying GE models.  

36. But, the puzzle is only apparent. Indeed, with a more sophisticated approach the supply elasticity can be consistently estimated. For example, Beck et al. (1991) derived supply elasticities based on Australian mine level cost data ranging from 2.7 to 3.5. They also estimated an aggregate coal supply elasticity ranging from 0.4 in the short term to 1.9 in the long run. This would support the view that the value of the coal supply elasticity is low, hence it could induce high carbon leakages. However, Beck et al. acknowledge the fact that their estimate only captures part of the response to the coal price. Other factors, notably price expectations can also play an important role. Moreover, their analysis does not take into account simultaneity of supply and demand. Mellish (1998), who elaborated a coal-pricing model based on an equilibrium framework overcomes the latter shortcoming. Using a two-stage least squares method, his estimates imply a response of the US coal supply to price with a relatively large elasticity of around 7. He also highlights the role of productivity gains in explaining the historical trends in the coal market. This could explain why over the long-run real prices have decreased while demand was steadily increasing.

37. The bottom-line is that econometric evidence is rather mixed. It could be noted that the estimates mentioned above are based on time-series regressions whereas, in principle, cross-sectional or pooled data regressions would be preferable for the calibration of GE models. They provide a better approximation of long-run relationships, which fit better with the structure underlying GE models.

7. Summary and concluding remarks

38. The aim of this paper was to provide a comprehensive analysis of the factors and mechanisms underlying so-called carbon leakages associated with a unilateral carbon emission reduction. We have used a simplified static GE model, calibrated on the OECD GREEN model. This approach made it possible to run multidimensional sensitivity analysis and therefore understand the interactions between different parameters over a wide range of values. The results point to some interesting findings:

- The non-energy trade channel has less effect on carbon leakage than it could be expected. Our simulation results showed that the leakage rate is not very sensitive to changes in the so-called Armington elasticities of substitution in non-energy markets. Similarly, the degree of international capital mobility does not affect leakages significantly. With a more elaborate description of the international capital markets, the G-Cubed model reports a similar result. It suggests that most of the capital reallocation induced by the implementation of the Kyoto Protocol would take place within Annex I countries rather than inducing capital flows

24. Using such a simple model and after correcting for serially correlated errors, Light et al. (1999) found a supply elasticity value that is not significantly different from zero.


26. This is an approximation, as the Mellish (1998) model has not been originally set up to estimate the supply response as a function of the price, but the reverse. However, given the large R2 of the equation both the direct and inverse specification of the supply elasticity should produce comparable results.
towards non-Annex 1 countries, therefore contributing little to carbon leakages (McKibbin et al., 1999).

- The key parameter is by far the supply elasticity of coal. Elasticity values above 4-5 yield small and relatively stable leakage rates, as obtained with the GREEN model. However, for lower values of the coal supply elasticity, the leakage rate increases rapidly. With the coal supply elasticity below one, the leakage rates can reach 40 per cent. As an extreme case, which also provides the intuition behind this result, a totally inelastic supply of carbon fuels would make it impossible to reduce world carbon emissions: the leakage rate of any unilateral abatement would be 100 per cent.

- The supply elasticity of coal is much more influential than the degree of substitutability in the international market between coal of different origins. In the GREEN model coal is treated as an quasi homogenous good but, as the analysis above showed, this assumption does not influence the leakage rate. With a high coal supply elasticity the leakage rates is small whatever the degree of substitution in the international coal market. The degree of integration in the international coal market only becomes influential under very low - probably unrealistic - values for the supply elasticity of coal.

- Finally, the shape of the production function also matters, a fact that has attracted little attention so far in the literature. Relatively high values of inter-factor and inter-fuel substitution elasticities generate high carbon leakages even if the supply of coal is elastic. High substitutability amplifies the reduction of the carbon demand and the increase of demands for other factors, including carbon-free energy resources, leading to higher adjustments in international prices. The sensitivity analysis performed with the WorldScan model confirms this result (Bollen et al., 1999). However, such high substitution elasticities are outside the bounds of the usual values found in the econometric literature.

39. The bottom-line of the extensive sensitivity analysis carried out in this paper is that carbon leakages are likely to be small for the range of parameters most frequently quoted in the literature (and used to calibrate the GREEN model). This result may have strong implications for policy-making, as the presumption of small or moderate leakages in case of unilateral emission reductions would favour the formation of a world-wide coalition to stabilise climate. But, the results presented in this paper also show that this outcome depends strongly on the assumption that the supply of coal is fairly elastic over the medium term. The number of coal mines closed down in Europe and other OECD countries in recent years support that hypothesis. However, more empirical work on the supply response of coal and oil producers would be needed to strengthen this conclusion.
REFERENCES


Table 1: Estimates of leakage rates\(^{(1)}\) associated with the implementation of the Kyoto Protocol

<table>
<thead>
<tr>
<th></th>
<th>Leakage rate in 2010(^{(1)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light et al. (1999)</td>
<td>21%</td>
</tr>
<tr>
<td>WorldScan(^{(2)})</td>
<td>20%</td>
</tr>
<tr>
<td>Merge(^{(3)})</td>
<td>20%</td>
</tr>
<tr>
<td>EPPA-MIT(^{(4)})</td>
<td>6%</td>
</tr>
<tr>
<td>G-Cubed(^{(5)})</td>
<td>6%</td>
</tr>
<tr>
<td>GREEN(^{(6)})</td>
<td>5%</td>
</tr>
<tr>
<td>GREEN(^{(7)})</td>
<td>2%</td>
</tr>
</tbody>
</table>

1. calculated as the ratio of the additional emissions in non-Annex 1 countries to the emission reduction in the Annex 1 countries.
6. This corresponds to a scenario without use of the flexibility mechanisms, see OECD, 1999.
7. Assuming full use of the "flexibility mechanisms" between Annex 1 countries; see OECD, 1999.

Table 2: Parameter values in the central case\(^{(1)}\)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trade substitution elasticity for the non-energy good</td>
<td>4</td>
</tr>
<tr>
<td>Capital mobility</td>
<td>0</td>
</tr>
<tr>
<td>Trade substitution elasticity for coal</td>
<td>5</td>
</tr>
<tr>
<td>Supply elasticity for coal</td>
<td>20</td>
</tr>
<tr>
<td>Supply elasticity for oil</td>
<td>1</td>
</tr>
<tr>
<td>Supply elasticity for the less carbon intensive energy</td>
<td>1</td>
</tr>
<tr>
<td>Interfuel substitution elasticity</td>
<td>2</td>
</tr>
<tr>
<td>Interfactor substitution elasticity</td>
<td>0.4</td>
</tr>
</tbody>
</table>

1. corresponding to the values used in GREEN
Table 3. Leakage rates simulated with GREEN under the Kyoto Protocol and various parameters’ assumptions

<table>
<thead>
<tr>
<th></th>
<th>S0</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
</tr>
</thead>
<tbody>
<tr>
<td>No permit trading</td>
<td>4.8%</td>
<td>22.9%</td>
<td>12.6%</td>
<td>27.3%</td>
<td>4.6%</td>
<td>5.1%</td>
</tr>
<tr>
<td>Permit trading</td>
<td>2.2%</td>
<td>17.4%</td>
<td>8.7%</td>
<td>21.5%</td>
<td>2.1%</td>
<td>2.5%</td>
</tr>
</tbody>
</table>

S0: central case specification with infinite (downward) supply elasticity of coal, supply elasticity of oil = 2, trade substitution elasticities for coal = 4-5 and oil treated as an homogenous commodity.
S1: supply elasticity of coal set at 0.1 all other parameters being as in S0.
S2: supply elasticity of coal set at 0.1 and trade substitution elasticity for coal = 0.5, all other parameters as in S0.
S3: supply elasticity of coal set at 0.1, supply elasticity of oil set at 0.5; all other parameters as in S0.
S4: trade substitution elasticities for coal = 0.5; all other parameters as in S0.
S5: trade substitution elasticities for coal = 10; all other parameters as in S0.

Source: OECD
Figure 1: Leakage rates as a function of two hypothetical parameters.

A: Impact of parameter $a$ not depending on parameter $b$.

B: Impact of parameter $a$ depending on the value of parameter $b$. 
Figure 2: Production structure of region 1.

- Output of the non-energy good
  - Energy bundle
    - Coal
    - Oil
    - Low-carbon energy
      - Region 1
      - Region 2
      - Region 1
  - Value added
    - Capital
      - Region 1
      - Region 2
      - Region 1
    - Labour and fixed factor
      - Region 1

Differentiation:
- Coal: differentiated
- Oil: homogenous
Figure 3. Leakage rates as a function of non-energy trade substitution elasticities and international capital mobility

NB: the label GREEN in the Figure correspond to the values of the parameters in the central case (see Table 2 in the text).
Figure 4. Leakage rates as a function of the supply elasticities for coal and oil

NB: the label GREEN in the Figure correspond to the values of the parameters in the central case (see Table 2 in the text).
Figure 5. Leakage rates as a function of the aggregate supply elasticities for coal and oil and the supply elasticity of the low-carbon energy

NB: the label GREEN in the Figure correspond to the values of the parameters in the central case (see Table 2 in the text).
Figure 6. Leakage rates as a function of the supply elasticity of coal and degree of differentiation on the international coal market

NB: the label GREEN in the Figure correspond to the values of the parameters in the central case (see Table 2 in the text).
Figure 7a. Leakage rates as a function of the inter-fuel substitution elasticity

Figure 7b. Leakage rates as a function of the inter-factor substitution elasticity

NB: the label GREEN in the Figure correspond to the values of the parameters in the central case (see Table 2 in the text).
Figure 8. **Leakage rates as a function of the interfuel and interfactor substitution elasticities**

NB: the label GREEN in the Figure correspond to the values of the parameters in the central case (see Table 2 in the text).
Figure 9. **World supply and international price of coal**

Source:

NB: IFS international Coal price deflated by the export values of industrial

*Source: IMF/IFS and*
ANNEX. SPECIFICATION OF A SIMPLIFIED GE FRAMEWORK

This annex provides the list of variables (Table A1), parameters (Table A2) and equations (below) of the simplified model used in the paper. All equations are expressed in a linearised growth rate form. All variables are expressed in per cent changes, except the carbon tax, the price levels and carbon emissions in the base period (marked in **bold**).

Energy supply

\[ S_{j,r} = \varepsilon_{j,r} \cdot (P_{j,r} - PVA_r) \quad \text{for } j = \text{coal, oil, } nC \text{ and } r = \text{Annex1, non-Annex1.} \]

Inter-regional capital allocation

\[ SK_r = \text{mig} \cdot (r_{-r}) \quad \text{with} \quad r = \sum r_{shk} \cdot r_r \quad \text{for } r = \text{Annex1, non-Annex1.} \]

Consumer prices of energy (including the carbon tax).

**Domestic price**

\[ P_{d_{j,r}} = \left( \frac{P_{d_{j,r}}^0 \cdot (1 + P_{j,r}) + \gamma_{j,r} \cdot CT_r}{P_{d_{j,r}}^0} \right)^{-1} \]

\[ \text{for } j = \text{coal, oil and } nC \text{ and } r = \text{Annex1, non-Annex1.} \]

**Import Price**

\[ P_{m_{j,r}} = \left( \frac{P_{m_{j,r}}^0 \cdot (1 + P_{j,r}) + \gamma_{j,r} \cdot CT_r}{P_{m_{j,r}}^0} \right)^{-1} \]

\[ \text{for } j = \text{coal, oil; } r \text{ and } r' = \text{Annex1, non-Annex1 and } r \neq r'. \]

**Note that for oil:** \( P_{\text{oil, Annex1}} = P_{\text{oil, non-Annex1}} \) and \( P_{\text{d_{oil,r}}} = P_{\text{m_{oil,r}}} \).

Composite Energy Prices

\[ P_{C_{j,r}} = \alpha d_{j,r} \cdot P_{d_{j,r}} + \alpha m_{j,r} \cdot P_{m_{j,r}} \]

\[ \text{for } j = \text{coal, oil and } nC \text{ and } r = \text{Annex1, non-Annex1.} \]

**Note that for nC:** \( P_{C_{nC,r}} = P_{d_{nC,r}} \).
(6) \[ PE_r = \sum_j \alpha_{j,r} \cdot PC_{j,r} \] for \( j = \text{coal, oil and nC} \) and \( r = \text{Annex1, non - Annex1} \)

Composite factor prices

(7) \[ PVA_r = \alpha L_r \cdot \omega_r + \alpha K_r \cdot \rho_r \] for \( r = \text{Annex1, non - Annex1} \).

Producer price of the non-energy good

(8) \[ P_r = \alpha E_r \cdot PE_r + \alpha VA_r \cdot PVA_r \] for \( r = \text{Annex1, non - Annex1} \).

Consumption of the non-energy commodity

(9) \[ C_{r,r'} = -\sigma_r \cdot P_r + (\sigma_r - 1) \cdot PC_r + Y_r \] for \( r \) and \( r' = \text{Annex1, non - Annex1} \).

and with \( PC_r = \beta_{r,r} \cdot P_r + \beta_{r,r'} \cdot P_{r'} \)

Output of the non-energy commodity

(10) \[ X_r = \sum_{r'} \delta_{r,r'} \cdot C_{r,r'} \] for \( r \) and \( r' = \text{Annex1, non - Annex1} \).

Total energy demand

(11) \[ E_r = -\kappa_r \cdot PE_r + \kappa_r \cdot P_r + X_r \] for \( r = \text{Annex1, non - Annex1} \)

Total demand of the composite factor (K,L)

(12) \[ VA_r = -\kappa_r \cdot PVA_r + \kappa_r \cdot P_r + X_r \] for \( r = \text{Annex1, non - Annex1} \)

Factor demands

(13a) \[ L_r = -w_r + PVA_r + VA_r \] for \( r = \text{Annex1, non - Annex1} \)

(13b) \[ K_r = -r_r + PVA_r + VA_r \] for \( r = \text{Annex1, non - Annex1} \)

Fuel specific demands

(14) \[ E_{j,r} = -\varphi_j \cdot PC_{j,r} + \varphi_j \cdot PE_r + E_r \] for \( j = \text{coal, oil and nC} \) and \( r = \text{Annex1, non - Annex1} \).
Demands for domestic and imported coal

\[
(15a) \quad Ed_{\text{coal}, r} = -\sigma_{\text{coal}, r} \cdot Pd_{\text{coal}, r} + \sigma_{\text{coal}, r} \cdot PC_{\text{coal}, r} + E_{\text{coal}, r} \quad \text{for } r = \text{Annex1, non} - \text{Annex1}.
\]

\[
(15b) \quad Em_{\text{coal}, r} = -\sigma_{\text{coal}, r} \cdot Pm_{\text{coal}, r} + \sigma_{\text{coal}, r} \cdot PC_{\text{coal}, r} + E_{\text{coal}, r} \quad \text{for } r = \text{Annex1, non} - \text{Annex1}.
\]

Coal production

\[
(16) \quad X_{\text{coal}, r} = shd_{\text{coal}, r} \cdot Ed_{\text{coal}, r} + she_{\text{coal}, r} \cdot Em_{\text{coal}, r}\quad \text{for } r \neq r' = \text{Annex1, non} - \text{Annex1}.
\]

World production of oil

\[
(17) \quad X_{\text{oil}} = \sum_r shd_{\text{oil}, r} \cdot E_{\text{oil}, r} \quad \text{for } r = \text{Annex1, non} - \text{Annex1}.
\]

Carbon emissions

\[
(18) \quad CEM_j = \sum_f \gamma_{f, j} \cdot X_{f, r} \cdot E_{f, r} \quad \text{for } j = \text{coal, oil and } nC \text{ and } r = \text{Annex1, non} - \text{Annex1}.
\]

Carbon tax revenues (in percentage of base-year GDP)

\[
(19) \quad RCTAX_r = \frac{(1 + CEM_j) \cdot CEM_j^0 \cdot CT_r}{Y^0_r} \quad \text{for } r = \text{Annex1, non} - \text{Annex1}.
\]

Regional incomes

\[
(20) \quad Y_r = (shL_r \cdot w_r) + (shK_r \cdot (r_r + SK_r)) + \sum_j sh_{j, r} \cdot (P_{j, r} + S_{j, r}) + RCTAX_r \quad \text{for } j = \text{coal, oil and } nC \text{ and } r = \text{Annex1, non} - \text{Annex1}.
\]

Market-clearing price of coal

\[
(21) \quad P_{\text{coal}, r} \quad \text{such as } S_{\text{coal}, r} = E_{\text{coal}, r} \quad \text{for } r = \text{Annex1, non} - \text{Annex1}.
\]

Market-clearing international price of oil
\[ P_{oil} \text{ such as } X_{oil} = \sum_{r} shs_{oil,r} \cdot S_{oil,r} \quad \text{and } P_{oil,r} = P_{oil} \]

for \( r = \text{Annex1, non – Annex1} \).

**Market-clearing price of the low-carbon energy**

\[ P_{nC,r} \text{ such as } S_{nC,r} = E_{nC,r} \quad \text{for } r = \text{Annex1, non – Annex1} \, . \]

**Market-clearing price of labour**

\[ w_r \text{ such as } L = 0 \quad \text{for } r = \text{Annex1, non – Annex1} \, . \]

**Market-clearing price of capital**

\[ r_r \text{ such as } K_r = SK_r \quad \text{for } r = \text{Annex1, non – Annex1} \, . \]
### Table A1. List of variables

<table>
<thead>
<tr>
<th>Equation number</th>
<th>Variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$S_{coal,r}, S_{oil,r}, S_{nC,r}$</td>
<td>Supply of coal, oil and the low-carbon energy (grouping gas, nuclear and other carbon-free energy sources)</td>
</tr>
<tr>
<td>2</td>
<td>$SK_r$</td>
<td>Supply of capital in region r</td>
</tr>
<tr>
<td>3</td>
<td>$r$</td>
<td>World composite rental price of capital</td>
</tr>
<tr>
<td>3</td>
<td>$CT_r$</td>
<td>Carbon tax in region r (in 1995 $ per ton of carbon)</td>
</tr>
<tr>
<td>3</td>
<td>$Pd_{coal,r}, Pd_{oil,r}, Pd_{nC,r}$</td>
<td>Domestic consumer prices for coal, oil and the low-carbon energy (including the carbon tax)</td>
</tr>
<tr>
<td>4</td>
<td>$Pm_{coal,r}, Pm_{oil,r}$</td>
<td>Import consumer prices for coal and oil (including the carbon tax)</td>
</tr>
<tr>
<td>5</td>
<td>$PC_{coal,r}, PC_{oil,r}, PC_{nC,r}$</td>
<td>Composite consumer prices for coal, oil and the low-carbon energy (including the carbon tax)</td>
</tr>
<tr>
<td>6</td>
<td>$PE_r$</td>
<td>Composite energy price in region r</td>
</tr>
<tr>
<td>7</td>
<td>$PVA_r$</td>
<td>Composite factor price in region r (corresponding to the composite price of labour and capital)</td>
</tr>
<tr>
<td>8</td>
<td>$P_r$</td>
<td>Producer price of the non-energy good in region r (corresponding to the composite price of the energy-factor bundle)</td>
</tr>
<tr>
<td>9</td>
<td>$PC_r$</td>
<td>Composite consumer price of the non-energy good in region r (corresponding to the composite price of domestic and imported demands for the non-energy good in region r)</td>
</tr>
<tr>
<td>9</td>
<td>$C_{r,r'}$</td>
<td>Consumption in country r of the non-energy good from region origin r'</td>
</tr>
<tr>
<td>10</td>
<td>$X_r$</td>
<td>Production of the non-energy good in region r</td>
</tr>
<tr>
<td>11</td>
<td>$E_r$</td>
<td>Total energy demand in region r</td>
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<tr>
<td>12</td>
<td>$VA_r$</td>
<td>Composite factor (K,L) demand in region r</td>
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<tr>
<td>13a</td>
<td>$L_r$</td>
<td>Labour demand in region r</td>
</tr>
<tr>
<td>14</td>
<td>$K_r$</td>
<td>Capital demand in region r</td>
</tr>
<tr>
<td>14</td>
<td>$E_{coal,r}, E_{oil,r}, E_{nC,r}$</td>
<td>Demands for coal, oil and the low-carbon energy in region r</td>
</tr>
<tr>
<td>15</td>
<td>$Ed_{coal,r}, Em_{coal,r}$</td>
<td>Domestic and imported demand for coal in region r</td>
</tr>
<tr>
<td>16</td>
<td>$X_{coal,r}$</td>
<td>Coal production in region r</td>
</tr>
<tr>
<td>17</td>
<td>$X_{oil}$</td>
<td>World production of oil</td>
</tr>
<tr>
<td>18</td>
<td>$CEM_r$</td>
<td>Carbon emissions (in tons of carbon) in region r</td>
</tr>
<tr>
<td>19</td>
<td>$RCTAX_r$</td>
<td>Revenues from carbon taxes in region r (expressed in percentage of the base year GDP)</td>
</tr>
<tr>
<td>20</td>
<td>$Y_r$</td>
<td>Income of region r</td>
</tr>
<tr>
<td>21-22-23</td>
<td>$P_{coal,r}, P_{oil,r}, P_{nC,r}$</td>
<td>Producer prices of coal, oil and the low-carbon energy (before tax)</td>
</tr>
<tr>
<td>24</td>
<td>$r_r$</td>
<td>Rental price of capital in region r</td>
</tr>
<tr>
<td>25</td>
<td>$w_r$</td>
<td>Wages in region r</td>
</tr>
</tbody>
</table>
Table A2. List of parameters

<table>
<thead>
<tr>
<th>Equation number</th>
<th>Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\varepsilon_{\text{coal},r}, \varepsilon_{\text{oil},r}, \varepsilon_{\text{nC},r}$</td>
<td>Supply elasticity for coal, oil and the low-carbon energy</td>
</tr>
<tr>
<td>2</td>
<td>$\mu_{ig}$</td>
<td>Elasticity of transformation for capital across regions.</td>
</tr>
<tr>
<td>3</td>
<td>$\gamma_{\text{coal},r}, \gamma_{\text{oil},r}, \gamma_{\text{nC},r}$</td>
<td>Emission coefficient for coal, oil and the low-carbon energy (in tons of carbon per Terajoule).</td>
</tr>
<tr>
<td>4</td>
<td>$P_{\text{coal},r}^0, P_{\text{oil},r}^0, P_{\text{nC},r}^0$</td>
<td>Levels of domestic energy prices in 1995 (in 1995$ per Terajoule).</td>
</tr>
<tr>
<td>5</td>
<td>$\alpha_{\text{coal},r}, \alpha_{\text{oil},r}, \alpha_{\text{nC},r}$</td>
<td>Share of domestic production in total consumption of coal, oil and the low-carbon energy. Note that $\alpha_{\text{nC},r} = 1$</td>
</tr>
<tr>
<td>6</td>
<td>$\alpha_{\text{coal},r}, \alpha_{\text{oil},r}, \alpha_{\text{nC},r}$</td>
<td>Share of imports in total consumption of coal and oil. Note that $\alpha_{\text{nC},r} = 0$</td>
</tr>
<tr>
<td>7</td>
<td>$\alpha_{K_{r},L_{r}}$</td>
<td>Shares of capital and labour in total value added of region $r$.</td>
</tr>
<tr>
<td>8</td>
<td>$\alpha_{E_{r},A_{r}VA_{r}}$</td>
<td>Shares of energy and value-added ($K, L$) in total production of the non-energy good in region $r$.</td>
</tr>
<tr>
<td>9</td>
<td>$\sigma_{r}$</td>
<td>Trade substitution elasticity (Armington) for the non-energy commodity in region $r$.</td>
</tr>
<tr>
<td>10</td>
<td>$\beta_{r,r'}$</td>
<td>Shares of domestic ($r'=r$) and foreign ($r' \neq r$) demands in total consumption of the non-energy commodity in region $r$.</td>
</tr>
<tr>
<td>11</td>
<td>$\delta_{r,r'}$</td>
<td>Shares of domestic demand ($\delta_{r,r'}$) and exports ($\delta_{r',r}$) in total output of the non-energy commodity produced in region $r$.</td>
</tr>
<tr>
<td>12</td>
<td>$\kappa_{r}$</td>
<td>Substitution elasticity between energy and value-added ($K,L$) in region $r$.</td>
</tr>
<tr>
<td>13</td>
<td>$\varphi_{r}$</td>
<td>Inter-fuel substitution elasticity in region $r$.</td>
</tr>
<tr>
<td>14</td>
<td>$\sigma_{\text{coal},r}$</td>
<td>Trade substitution elasticity (Armington) between domestic and imported coal in region $r$.</td>
</tr>
<tr>
<td>15</td>
<td>$sh_{\text{coal},r}, she_{\text{coal},r}$</td>
<td>Shares of domestic demand ($sh_{\text{coal},r}$) and exports ($she_{\text{coal},r}$) of coal in total coal output in region $r$.</td>
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<tr>
<td>16</td>
<td>$sh_{\text{oil},r}$</td>
<td>Shares of oil demand in region $r$ in total world oil consumption.</td>
</tr>
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<td>17</td>
<td>$\lambda_{\text{coal},r}, \lambda_{\text{oil},r}, \lambda_{\text{nC},r}$</td>
<td>Energy content (in Terajoule per 1995 $) for coal, oil and the low-carbon energy in region $r$.</td>
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<tr>
<td>18</td>
<td>$C_{\text{EM}}^{r}$</td>
<td>Level of carbon emissions in the base year 1995 in region $r$.</td>
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<td>$\gamma_{r}$</td>
<td>GDP level in the base year 1995 in region $r$.</td>
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<td>$sh_{L_{r}}, sh_{K_{r}}$</td>
<td>Shares of labour and capital in total GDP of region $r$</td>
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<td>21</td>
<td>$sh_{\text{coal},r}, sh_{\text{oil},r}, sh_{\text{nC},r}$</td>
<td>Shares of coal, oil and the low-carbon energy in total GDP of region $r$.</td>
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<tr>
<td>22</td>
<td>$sh_{\text{oil},r}$</td>
<td>Shares of oil production in region $r$ in total world production of oil.</td>
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