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Consumption-Based Approaches in International Climate Policy: An Analytical Evaluation of the Implications for Cost-Effectiveness, Carbon Leakage, and the International Income Distribution

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Abstract

As an agreement on an international climate treaty appears out of sight in the short run, many countries rely on unilateral greenhouse gas abatement strategies. The reach of such unilateral policies can be extended beyond the borders of the abating country by a switch to a consumption-based policy orientation. Such a policy does not target the emissions discharged on the territory of the country that abates, but the emissions embodied in the goods it consumes. If industrialized countries adopt this approach, they can bring the large and increasing amount of emissions embodied in imports from emerging economies into the scope of the policy. The policy switch could be implemented by means of border carbon adjustments; according to theoretic arguments such adjustments can improve the efficiency of unilateral policies. This paper develops a 2-region, 5-good analytical partial-equilibrium model to study the effects of a switch of the policy base. We especially focus on changes in production technology triggered by the policy. We find that a policy targeting consumption – when using a leakage definition appropriate for consumption-based approaches – does not cause leakage through the non-energy market leakage channel. In addition, the question whether a consumption-based policy is environmentally more effective is decided through policy transmission in non-energy markets, but not in energy markets. Still, despite the many arguments in favour of consumption-based approaches, we find that none of these arguments per se suffices to make a consumption-based policy the environmentally more effective or the more cost-effective option. Whether it is indeed more effective depends on (i) demand and production parameters and (ii) the precise design of the border tax (or any other appropriate policy instrument). In particular, the availability of "green" technology in emerging economies influences the results. Additionally, a switch of the policy base may also cause a substantial redistribution of the costs of the policy between abating and non-abating countries.

Keywords: Unilateral climate policy, consumption-based accounting, carbon leakage, border carbon adjustments, trade and environment

JEL Codes: Q54; Q56; F18; H23.

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1 Introduction

International climate policy is currently characterized by the absence of a worldwide coordinated emissions abatement strategy. The UN climate conference in Durban in 2011 envisioned work on an international climate treaty, and the recent UN conference in Doha in December 2012 affirmed that goal (UNFCCC 2011c, 2012); but that treaty – if ever signed – is supposed to enter into force not before 2020. Thus, at least in the short to medium term global climate policy will be dominated by unilateral actions of single countries or groups of countries like the European Union. Such unilateral climate policy is typically less effective in slowing climate change than an internationally coordinated effort. Still, even unilateral policy measures have the potential to influence emissions abroad. Therefore, it is sometimes argued, countries pursuing a unilateral policy could improve the global effectiveness of their policy by making better use of this potential. In particular, a switch from policies targeting territorial emissions to what has been termed consumption-based approaches is being discussed. Employing a stylized analytical model, this article analyzes the consequences of such a policy switch for the effectiveness of the policy and for international income distribution.

A commonly used criterion to evaluate the effectiveness of a policy is its cost-effectiveness. It is easy to see why unilateral policy approaches are typically not cost-effective: global cost-effectiveness requires that emissions be abated in those countries where it is cheapest to do so (Weyant and Hill 1999). This is sometimes termed “where-flexibility”. By proceeding unilaterally, a country foregoes the potentially huge cost-savings from exploiting this where-flexibility. This especially applies to industrialized countries: Many of them have already partly decarbonised their economy and therefore now face high marginal abatement costs, whereas the marginal abatement costs in countries without any emission control – like some developing and emerging economies – are still close to zero (Barrett 1998, Stern 2007).

A second problem of unilateral mitigation – typically related to cost-effectiveness – is carbon leakage. As global warming is caused by the global concentration of greenhouse gases (GHGs), the success of a mitigation policy depends on its effect on the sum of emissions in all countries world-wide, and not just on the amount of GHG reduction in the country pursuing the policy. Strict limits on emissions in one country, however, may lead to an increase in emissions in other countries. Emissions thus are merely shifted across borders instead of being reduced on the global level. The main reason for such carbon leakage is, on the one hand, that abatement typically raises the costs of products subject to the policy; and that in turn induces consumers and buyers of intermediate products to substitute products not targeted by policy for these now more expensive products. Additionally, as most CO_2 emissions stem from the burning of fossil fuels, climate policy reduces demand for fossil fuel in the region that abates, which depresses world market prices for fossil fuels. That, however, causes a rise in fuel use elsewhere. Both effects thus lead to an increase of emissions in countries that do not abate, thereby counteracting the original GHG mitigation effort.

If a first-best solution to these problems (like the introduction of a globally uniform carbon price) is out of sight and a region nonetheless wants to go ahead with a unilateral climate policy, naturally it must make a choice between different second-best policies. One dimension in this choice will be the question which emissions the country or region should target with its policy. Currently, virtually all countries apply their climate policy to the emissions directly discharged on their territory. For emissions set free in the production of goods and services, this means counting the emissions at the point of production of these goods, irrespective of where and by whom the goods are later consumed. Emission counted following this principle are therefore often referred to as the country's "production-based emissions inventory" (e.g. Peters and Hertwich, 2008a). Territorial or production-based emissions accounting is also the GHG accounting principle employed by the UNFCCC in the Kyoto Protocol. However, it is not the only possible accounting principle: Alternatively, one might record emissions at the point where goods and services are consumed. All emissions that occurred in any location worldwide in the course of the production of these goods would then be attributed to this consumption. This is termed "consumption-based accounting", and the emissions base thus determined can also be used as base for unilateral climate policy: for example, a tax could be levied on the emissions "embodied" in every good sold for consumption. Thirdly, one can also attribute emissions to the suppliers of primary inputs that "enabled" emissions by their supply decisions (Lenzen and Murray 2010). For example, the owners of fossil fuel deposits enable emissions by supplying oil – and receive income in return for their provision of this natural resource. This perspective on emissions has therefore recently been termed "income-based responsibility" (Marques et al. 2012).

Here, we however focus on comparing the current production-based to the consumption-based approach, as a switch to using consumption as the policy base has been suggested as a possible means to reduce leakage and increase the cost-effectiveness of a policy. First, note that for the world as a whole both emissions measures – the production-based and the consumption-based one – are equal: They record exactly the same emissions, just at different points. For an individual country however, the two measures typically diverge. This is due to the fact that emissions embodied in imports are brought into the country. When the imported goods are consumed in that country, these emissions will be recorded as part of the country's consumption-based emissions inventory, but – as these goods where produced in a different part of the world – they are not counted as part of the country's production-based emissions inventory. The opposite holds true for goods exported: the emissions set free in their production are recorded in the exporting country's production-based emissions inventory but not in its consumption-based one. Thus, the difference between a policy using production and one using consumption as its base is that the first policy targets the country's exports and the second the country's imports. Both policies, of course, also include the country's domestic production for domestic consumption in their bases.

Two lines of the economic literature explicitly or implicitly discuss a switch to a consumption-based policy orientation. First, in the literature on emissions embodied in trade consumption-based approaches are often favored as being "fairer" (Kondo et al. 1998, Munksgaard and Pedersen 2001, Ferng 2003, Bastianoni et al. 2004, Peters and Hertwich 2006). Additionally, basing international climate policy on consumption-based accounting is seen as a means to counter the current trend of an increase of carbon imports by industrialized countries, which leads to an increase of emissions in countries without binding mitigation policies (Peters and Hertwich 2008a,b, Nakano et al 2009, Wiedmann 2009). This argument suggests that in the current international situation a consumption-based policy approach might be the environmentally more effective one.

Second, the literature on carbon border adjustments indirectly also discusses switching to a consumption-based approach – although in that strand of literature it is usually not termed that way. Carbon border adjustments work as follows: the region that abates bases its policy on production-based emissions accounting, but supplements that policy by import taxes and export rebates. The import taxes are levied on the carbon-content of products originating from countries not following an equally stringent climate policy, and the export subsidies are granted to domestic producers for the carbon content of exports to countries with a less stringent policy. If such import taxes and export rebates are applied to all products according to their true carbon content and if the carbon price charged or rebated equals the domestic carbon price, the measures represents a full switch to a consumption-based policy approach; or, to use the language of the literature on international taxation, a switch from a origin basis to a destination basis in the carbon tax system.

Economic theory suggests that border adjustments improve the economic efficiency of unilateral climate policy measures (Markusen 1975, Hoel 1996, Gros 2009). In recent years such measures have however mostly been discussed for other reasons: industry representatives and politicians sometimes favor them because of fears that unilateral climate policy might lead to a loss of competitiveness of the domestic industry (Clapp, 2010). The results of simulation studies on the performance of border adjustments according to these various criteria are mixed: Analyses focusing on individual energy intensive sectors in general support the view that border adjustments reduce competitiveness losses (see e.g. Monjon and Quirion 2009). Most – but not all – computable general equilibrium studies come to a similar conclusion (see e.g. Boehringer et al. 2012, but also Burniaux et al. 2010 for a contrarian result). Many analyses also see at least some reduction of carbon leakage. According to a recent study comparing 12 simulation models, border measures however only bring about modest improvements in terms of cost-effectiveness. On the other hand, they shift the economic burden of emissions reduction to non-abating countries (Boehringer et al. 2012a).

As it is currently mostly industrialized countries that have implemented or plan to implement unilateral policies, a switch to a consumption-based policy may thus impose additional costs on developing and emerging economies. Such a result may not only be deemed unfavorable for reasons of justice, it might also block progress in international climate negotiations or trigger retaliatory measures by emerging economies. Thus, effects on the international distribution of income may prove to be an important argument for or against the adoption of consumption-based policy approaches.

In this article, we therefore examine such distributional impacts. The main focus of the following analysis, however, is a comparison of the effectiveness of policies targeting either emissions in production or in consumption. To this end, we will develop a stylized analytical partial equilibrium model that includes two regions, four final goods markets, and a global fossil fuel market. This model-based, theoretic approach was chosen for the following reasons: The literature on emissions embodied in trade does not employ theoretic models to study the effects of different policies; and the more recent economic literature on carbon border adjustments mostly uses computable general equilibrium (CGE) models. These models aim to provide realistic estimates of parameter values, but due to their complexity they are often less well suited to reveal the basic economic mechanisms that determine the effectiveness of different policies. For that task, simple analytical models might be helpful.

There already exists an earlier literature that employs such analytical models to study optimal unilateral taxation in case of international externalities. That literature to this day figures as the theoretical basis of the analysis of carbon border adjustments – we will discuss it in more detail in section 2. In this article, the focus is on some issues of unilateral abatement policies that have not been treated in the existing analytical literature in detail: first, the relationship between the policy evaluation criteria of cost-effectiveness and carbon leakage. We will also argue that the concept of carbon leakage cannot be employed for policies targeting consumption-based emissions in the same way as for policies targeting production-based emissions. Second, we will allow the policy to trigger changes in production technology. Much of the existing analytical literature takes production technology as given. Under this assumption, a policy that targets emissions in the exports of non-abating countries will necessarily lead to a drop of these exports and in turn probably to income losses for these countries. Naturally, such a policy is heavily opposed by non-abating countries (see e.g. Voituriez and Wang 2011 for the Chinese position). In this paper, we examine whether the costs of the policy can be reduced by allowing for a "greening" of the production technology in countries not following the policy as a – probably politically more acceptable – alternative to curbing the exports of these countries. Third, the leakage literature usually distinguishes between effects of the policy in energy and in non-energy markets. We will analyse the interrelationship of policy transmissions in these two classes of markets.

The remainder of this paper is organized as follows: Section 2 reviews the existing theoretical literature on economic efficiency and carbon leakage in situations where one region follows a unilateral policy in the presence of international externalities. Section 3 gives an overview of the differences between production-based and consumption-based emissions accounting and discusses the policy evaluation criteria of cost-effectiveness, environmental effectiveness and carbon leakage. Section 4 introduces the analytical climate policy model. Section 5 employs this model to compare the effects of production-based and consumption-based approaches in non-energy markets; and section 6 extends the analysis by the inclusion of energy markets. Finally, section 7 summarizes the results and concludes.

2 Unilateral climate policy – theoretical background

Conceptually, the unilateral pursuit of an abatement policy can be framed as a problem of optimal unilateral taxation to correct a global externality. Markusen (1975) analyzes such a setting in a simple two-country, two-good general equilibrium model. In this model, production results in a fixed level of pollution per unit of output. Welfare in one of the two countries, the "domestic country", depends on consumption as well as on the global level of pollution. The country has three policy instruments at its disposal: a production tax, a consumption tax, and border adjustments (tariffs or subsidies). It will use these instruments to influence the global level of pollution. Now, Markusen derives results for the welfare optimum of the domestic country (but not the global welfare optimum). He shows that this optimum can be achieved by any combination of two of the three policy instruments, e.g. by combining either a production tax or a consumption tax with border adjustments (or by combining a production and a consumption tax). Note that in this setting neither a policy with production as its base nor one with consumption at its base alone suffices to reach the welfare optimum – both policies need to be combined with border adjustments, and these adjustments are not "full adjustments" (in the sense as discussed in section 1, i.e. adjustments that achieve a complete switch of the policy base).

The "mechanism" in that type of model by which a country influences the level of emissions in a foreign country is the following: the tax imposed by the domestic country influences the world price of the polluting good, and this price in turn has an effect on foreign production and thus foreign pollution. Note that for this mechanism to work the country using it must have some "monopoly power" in international trade, i.e. it must be able to influence international prices. If the domestic country has no monopoly power and is limited to use just one of the three instruments, it should use a production tax. Thereby it can reach the welfare optimum. By a consumption tax, on the other hand, in this setting the country cannot influence world prices and therefore neither can it influence domestic nor foreign production. Thus, the optimal consumption tax is zero. Finally, if the country is limited to use just one of the three instruments but has monopoly power, it is – as Markusen shows – not possible to rank these three "second-best" instruments in terms of welfare.

Hoel (1996) extends Markusen's results to a more general n-country, n-good setting. He finds that a unilaterally abating coalition of countries can achieve its welfare optimum by combining a domestic uniform carbon tax on emissions in production with border adjustments. Both Markusen and Hoel derive expressions for the optimal border tariff (or subsidy) that share the following characteristics: they consist of a term that represents the terms of trade effect and an (additive) second term that represents the effect of the border tax on foreign emissions. The terms of trade term is simply the optimal tariff formula known from international trade theory: a country that has some monopoly power in international trade can in general improve its welfare by taxing its imports. It therefore has a motive for imposing border taxes independent of any effect these taxes may have on emissions. The foreign emissions term represents the price effect on foreign emissions described in the previous paragraph. According to Hoel, for each good this term is proportional to (i) the domestic carbon tax and to (ii) the marginal effect that a reduction of net imports of that good has on total foreign emissions. If one analyses not the welfare of the abating coalition (like Hoel) but global welfare, the terms of trade term vanishes. Thus, in that case the optimal border tax depends only on the foreign emissions term (Boehringer et al. 2012b). The globally welfare maximizing border carbon tax therefore is proportional to but not the same as the domestic carbon tax: the border tax is higher the larger its effect is on foreign emissions reduction, and this effect is in general different for different goods. Also, in Hoel's model this effect does not only depend on emissions embodied in the good examined, but also on emissions embodied in other foreign goods. This is due to the fact that the production of these other goods may increase and replace the production of the good examined, if the international price of this good is lowered by means of the import tax. Low-carbon goods should therefore not be taxed at the border, but in some cases even subsidized, as an increased foreign production of these goods will crowd out the more emissions-intensive production of other foreign goods. Summarizing the principal point, from a global perspective it is in general not optimal to apply the same carbon price used in the taxation of domestic products also in the calculation of border taxes.

More recently, Gros (2009) has also analyzed the welfare effects of carbon border taxes. In contrast to Markusen and Hoel, Gros determines global welfare, and not just the welfare of the country abating. He employs a simple, one-good, two-country partial equilibrium model. Production of the good leads to CO_2 emissions at a fixed per unit rate. These emissions lower global welfare. The good examined is imported by the country following the climate policy; and the type of border adjustment studied consist only of an import tax (but not an export rebate, as there is no export good in this model). The main finding of the analysis is that the introduction of the border tax increases global welfare if there is insufficient carbon pricing abroad. In the welfare optimum, the domestic carbon tax and the carbon border tax are, however, not equal to the social cost of the externality, and they are also not equal to each other: the domestic tax is higher, and the border tariff is lower than the social cost of CO_2 emissions. Thus, the imposition of the optimal border tariff will not completely "level the playing field" (as is sometimes demanded by industry representatives) for domestic and foreign producers. In general, the optimal level of the border tariff depends on many parameters such as the carbon intensity abroad, the relative sizes of the production bases in the two countries, and the elasticities of demand and supply of the good examined.

A somewhat different approach is chosen by Fischer and Fox (2012). They do not investigate the efficiency of certain policy measures, but their effect on global emission reduction, carbon leakage, and competitiveness. Also, they interpret their findings as relating to individual carbon-intensive sectors of an economy, but not to the economy as a whole. More specifically, Fischer and Fox are interested in the effects of various anti-leakage policies, among them also full-border adjustment – which, as argued in the introduction to this paper, can be seen as a switch from production- to consumption-based accounting. They develop a two-country, two-good partial equilibrium model. Climate policy is introduced by a domestic carbon tax, which is then complemented with an import tax and an export subsidy. The policy affects production- and consumption-levels and the carbon intensity in domestic, but not in foreign production. The main finding is that carbon border adjustments support competitiveness, but the results for the effect on global emissions are less clear-cut. Whether a policy with or without border adjustments leads to a larger reduction in global emissions depends on the relative carbon intensities in the two countries studied, on elasticities of substitution, and on consumption volumes.

Summarizing, most of the studies discussed in this section find that the optimal unilateral policy to correct a global externality actually is neither a policy with just production nor one with just consumption as its base, but a policy combining either of the two approaches with "less than full" border adjustments. In this article, we will however not examine such "mixed" policies but confine our analyses to comparing a policy with a "pure" production tax to one with a "pure" consumption tax.

3 Emissions accounting, policy effectiveness, and carbon leakage

After the UN climate conferences in Copenhagen and Cancun in 2009 and 2010, around 90 countries have offered various GHG mitigation pledges.[1] If these countries abide by their pledges, a multitude of national climate policies with quite different levels of stringency will

[1] See UNFCCC, 2011a, for an overview of the mitigation pledges of the developed countries, and UNFCCC, 2011b, for an overview of the mitigation pledges of the developing countries.

exist side by side. Here, we will not attempt to model this real-world complexity. Rather, we look at the simplest of possible settings to analyze the consequences of a switch of the GHG accounting system: a world, where one region (the policy-region, called "Home" in the following) pursues a GHG abatement policy, whereas the rest of the world (the non-policy region, called "Foreign" in the following) does not. In a highly stylized representation of current international circumstances, we assume that the policy region Home comprises industrialized countries, whereas the non-policy region Foreign consists of developing and emerging economies. The carbon intensity in production in Foreign is assumed to be substantially higher than in Home.[2] Furthermore, in the model-based analysis of this paper, we will assume a highly simplified production structure: Only final (but no intermediate) goods are manufactured and traded.

3.1 Emissions accounting concepts

Employing this simplified framework, we can now define the various emissions accounting concepts. Region Home produces goods for domestic consumption as well as for export, denoted by H and X, respectively. Foreign produces goods for its domestic consumption (F), and also goods it exports (termed M, as these goods are imports seen from the perspective of Home). Let now E_H be the GHG emissions discharged by producing H, E_X those discharged by producing X, E_F those discharged by producing F, and E_M those discharged by producing M. Then, Home's production-based emissions inventory E_1^{PB} and Foreign's production-based emissions inventory E_2^{PB} are defined as follows (variables and parameters relating to region Home will in the following be marked by the subscript 1, those relating to Foreign by the subscript 2):

$$E_1^{PB} = E_H + E_X \,, \tag{3.1}$$

$$E_2^{PB} = E_F + E_M \,. \tag{3.2}$$

E_1^{PB} includes all emissions set free to produce Home's output, and E_2^{PB} includes those set free to produce Foreign's output.[3, 4]

[2] The literature on emissions embodied in trade finds that the emissions intensity of imports by industrialized countries from developing or emerging economies typically far exceeds the average emissions intensity of the importer's own industry. Peters and Hertwich (2006), for example, estimate for the case of Norway that one would underestimate emissions embodied in imports by a factor of 2.5, if one were to assume that imports are produced with Norwegian technology. Davis and Caldeira (2010) and Boehringer et al. (2011) provide an overview of such differences in carbon intensities between industrialized and developing countries. In our model, if region Home represents a group of industrialized countries and Foreign the rest of the world, the assumption of the emissions intensity in Foreign exceeding the one in Home thus accurately reflects real-world circumstances.

[3] Definitions 3.1 and 3.2 only apply to a simplified emissions accounting concept without intermediate goods. The difference between this simplified concept employed here and a realistic setting with intermediate goods is that in the realistic setting exports are a gross quantity - they comprise value-added from domestic production as well as value-added that was imported. Only the part of exports that stems from domestic production is counted towards a country's production-based emissions inventory (Peters 2008).

[4] As Peters (2008) and Peters and Hertwich (2008a, b) point out, the definition of the production-based emissions inventory used in the literature on emissions embodied in trade (which is the one used in this article) is close, but it is not exactly the same as the one employed by the UNFCCC in the Kyoto Protocol (UNFCCC, 1997;

Because of international trade, the goods a country consumes are not all the same as the ones it produces. For region Home, imports M bring additional goods for consumption into the region, and exports X take goods produced in Home out of the region. Thus, Home's consumption-based emissions inventory[5] differs from its production-based one. It comprises all emissions discharged in the production of the goods Home consumes, irrespective of where this production took place (in Home or in Foreign). The exact definitions for the two consumption-based emissions inventories ${E_1}^{CB}$ and ${E_2}^{CB}$ are as follows:[6, 7]

$$E_1^{CB} = E_H + E_M \tag{3.3}$$

$$E_2^{CB} = E_F + E_X \tag{3.4}$$

The two different emissions inventories can now both be used as a policy-base for GHG mitigation policies, i.e. policy targets and policy instruments can either be tied to a country's production-based or to its consumption-based emissions. We will in the following refer to these two options as "production-based policy" and "consumption-based policy".[8]

3.2 *Climate policy evaluation criteria*

Our aim is to determine whether the choice of policy base makes a difference for the effectiveness of the policy. Most of the studies discussed in section 2 compare policies according to the criterion of economic efficiency. This is the criterion of choice for a purely theoretical analysis; for an analysis closer to real-world circumstances it is however difficult to implement – to use it in a practical setting one must value different environmental outcomes, which is a difficult and controversial exercise. We will therefore use criteria that avoid such a valuation. The IPCC lists two policy evaluation criteria that refer to policy-effectiveness: environmental effectiveness and cost-effectiveness (IPCC, 2007). Additionally,

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UNFCCC, 1998). For example, the UNFCCC definition does not assign emissions from international transportation to any country. For the topics discussed in this article, however, the difference between the two definitions is inconsequential and will therefore not be elaborated.

[5] Note that in the term "consumption-based emissions" the word "consumption" is used in a different sense than in national income accounting: it refers not only to private consumption, but also to investment and to government consumption, i.e. to all forms of domestic final demand.

[6] Again, the definition would be different for a setting that also includes intermediate goods: In that case, imports would contain (a) final goods as well as (b) intermediate goods. The intermediate goods can be used to produce either (b1) domestic final goods or (b2) exports (Peters, 2008). Only (a) and (b1) are part of Home's final demand. So only (a) and (b1) are counted towards a country's consumption-based emissions inventory.

[7] Emissions discharged not during production but during the final use of goods (like emissions from the use of private cars or from heating private homes) can be included in the production-based as well as in the consumption-based emissions inventory of the country where these emissions are set free. In the model developed in this article, we will however assume that all emissions occur in production.

[8] Most countries currently abating their GHG emissions follow a production-based policy. In practical terms, this means imposing the carbon price (e.g. a tax or the costs of emissions permits) on those firms that actually discharge the GHGs. Consumption-based policies are currently not followed by any country on a wider scale. The academic literature however discusses several options how they might eventually be introduced (see e.g. Droege 2011b, Droege et al. 2009). The only one of these options that could be realized relatively quickly appear to be border carbon adjustments (which were briefly discussed in the introduction). In this article, we will however not elaborate on the practical issues of an eventual transition to a consumption-based policy orientation. We instead focus on the economic consequences of such a switch of policy base.

both in the academic literature and in political discussions the criterion of carbon leakage is widely used. We will briefly discuss all three of these criteria.

Cost-effectiveness is a criterion favored by many economists, as it evaluates both the costs and the benefits of a policy. Here, we are interested in the question whether a certain climate policy is desirable for the world as a whole – therefore benefits as well as costs must be measured on a global level, even if it is just one region that pursues the policy. Benefits in this analysis will be represented by the reduction in global CO_2 emissions.[9] Then, the most cost-effective policy is the one that achieves either a given reduction of global emissions at the least global costs or the largest reduction in global emission at given global costs.

Environmental effectiveness, on the other hand, is a criterion that only looks at the benefit side of a policy: the IPCC (2007) defines it as the extent to which a policy meets its intended environmental objective. In this analysis, the environmental objective is again given by the reduction of global CO_2 emissions. As no information on the costs of the policies examined is required, environmental effectiveness may be a criterion that is more convenient to apply in practical circumstances than cost-effectiveness; this convenience, however, comes at a price: the informative value of a comparison of the environmental effectiveness of two policies is, of course, smaller than that of a comparison of their cost-effectiveness. For a comparison of environmental effectiveness to make sense, the two policies being compared also have to be similar at least regarding some of their aspects: we will in the following compare policies that either (i) achieve the same emissions reduction within the policy region or that (ii) impose the same carbon price. As we will see in section 5.6, option (ii) actually can be interpreted as a simple cost-effectiveness analysis.

For the third criterion, *carbon leakage*, various definitions exist. Here, the variant termed "policy-induced carbon leakage" (Droege 2011) or "strong carbon leakage" (Peters and Hertwich 2008a) shall be employed, as this variant is related to the concept of policy-effectiveness. Policy-induced carbon leakage is defined as the increase in emissions in the non-policy region following the introduction of the policy, compared to a reference situation without the policy.[10] Such an increase of emissions in the non-policy region can be regarded as an unwanted "side-effect" of the policy: a mere shift of emissions from the policy region to the non-policy region that does not help to lower emissions on a global level. In this way carbon leakage diminishes the effectiveness of the policy in reducing global emissions.

Note, however, that by looking at carbon leakage alone it is not possible to judge the overall environmental effectiveness of a policy. Carbon leakage is only a measure of the effect of the policy in the non-policy region. But to assess the environmental effectiveness of a policy, one must gauge the effect of the policy both in the non-policy and in the policy-region. It may well be the case that a comparison of policies gives the following result: policy *A* leads to a little less leakage than policy *B*. But policy *B* is much better in lowering emissions in the policy region than policy *A*. Taken together, policy *B* causes a larger reduction in global emissions and is therefore the environmentally more effective one, even

[9] We thus limit our discussion to just one of the GHGs, albeit the most important one. Also, to simplify the analysis, we define benefits in terms of the "intermediate goal" of global emissions reduction, and not in terms of a reduction of global GHG concentrations or even of climate change impacts avoided.

[10] The IPCC defines carbon leakage as "the part of emission reductions in Annex B countries that may be offset by an increase of the emissions in the non-constrained countries above their baseline levels" (IPCC, 2007).

though it performs worse as regards leakage. In one specific setting it is however indeed possible to infer the environmental effectiveness of a policy directly from its leakage ratio: if one compares two policy that bring about an equal emissions reduction in the policy region, then the policy involving less leakage leads to a larger reduction in global emissions and is therefore indeed the environmentally more effective one.

Let us now exactly define leakage for our two-region framework. In its most simple form, policy-induced leakage can be stated in absolute terms, i.e. in tons or megatons of CO_2 of additional emissions in the non-policy region. If Home introduces a policy using production as the policy-base, then the policy area consists of $H + X$ and the non policy-area of $F + M$. The absolute policy-induced leakage for a policy targeting production, L^{PB}, thus equals[11]

$$L^{PB} = \Delta E_F + \Delta E_M \,. \tag{3.5}$$

Δ denotes the change in a variable compared to the situation before the introduction of the policy. Absolute leakage therefore is a measure of the (unintended) side-effect of the policy, an increase of emissions in the non-policy region, in absolute terms.

However, more common than this absolute leakage measure is a relative measure – the leakage ratio (denoted here by the lower-case letter l). It is defined as the increase of emissions in the non-policy area divided by the reduction in the policy area:

$$l^{PB} = \frac{\Delta E_F + \Delta E_M}{-(\Delta E_H + \Delta E_X)} \,. \tag{3.6}$$

Thus the leakage ratio sets the undesired effect of the policy – the increase of emissions in the non-policy region – in relation to the desired effect, the reduction of emissions in the policy-region.

To serve as such a measure of the unintended effect of the policy, the leakage formula must be adapted if Home switches to a policy with consumption as the base: such a policy targets emissions embodied in $H + M$ – thus the intended effect of the policy is a reduction of these emissions. And the unintended effect of the policy is a possible increase of emissions outside this "consumption policy-base", i.e. in sectors $F + X$. Absolute leakage and the leakage ratio for a policy with consumption as the base are thus defined as follows:

$$L^{CB} = \Delta E_F + \Delta E_X \,, \tag{3.7}$$

[11] All leakage definitions given here only apply to a (simplified model) setting without intermediate production. If one were to include production and trade in intermediate goods, all variables in the leakage formulas referring to imports or exports would have to be adjusted; see Footnotes 3 and 6 for details.

$$l^{CB} = \frac{\Delta E_F + \Delta E_X}{-(\Delta E_H + \Delta E_M)} \ . \qquad (3.8)$$

When comparing policies, one therefore has to decide whether to calculate leakage with the "production formulas" 3.5 and 3.6 or with the "consumption formulas" 3.7 and 3.8. The choice between these formulas should be guided by the aim a country pursues with its climate policy, and not by the base of the actual policy followed, i.e. the emissions reduction target that a country wants to reach defines what is an "intended" and what an "unintended" effect (Steininger et al. 2012). Assume, for example, that a country, bound under the current UNFCCC system by mitigation targets referring to emissions in production, decides to introduce border carbon adjustments to protect its domestic industry. The border adjustments in effect represent a switch to a consumption-based policy. Now the country wants to know whether leakage under its former production-based or its new consumption-based policy is larger. In this case, the country should calculate leakage for both policies with the "production formulas" 3.5 and 3.6, as with both policies it aims to reach a mitigation target stated in terms of production. This also is the scenario usually assumed in the CGE literature on border carbon adjustments (see e.g. Boehringer et al. 2010a, 2012, Burniaux et al. 2010, Fischer and Fox 2012). Note, however, that the leakage measure calculated in this way provides information only on the question how well the policy performs in achieving the country's internationally agreed mitigation target, but not on whether the policy also helps to reduce global emissions.

The situation, however, changes if a country wants to analyze a change of both policy and target base – either because a switch of the global accounting system is considered or because the country is interested in how by pursuing a unilateral policy it best furthers mitigation efforts on the global level. Then, leakage for the production-based policy should be determined by formulas 3.5 and 3.6, and leakage for the consumption-based policy by formulas 3.7 and 3.8. For much of the remainder of this article, we will proceed in exactly that way: we will analyze a switch of both the target and the policy base, as we are interested in the unintended effects of policies as seen from a global perspective.

3.3 Climate policy transmissions channels

This section gives a brief overview of the economic "mechanisms" by which climate policy achieves its aim of emissions reduction. The leakage literature often categorizes leakage effects along what it terms "leakage channels". Typically, at least two such channels are identified: the non-energy market and the energy market leakage channel (see e.g. Burniaux and Oliveira Martins 2011). These channels, however, cannot only be employed to study carbon leakage, we can also use them to structure our discussion of the effects of a climate policy in general: we will thus distinguish between climate policy transmission in non-energy markets and in energy-markets.

Energy markets are directly affected by any mitigation policy, as the burning of fossil fuels like oil, gas, or coal is by far the most important source of CO_2 emissions. The introduction of a carbon price in the policy region (by means of a tax or tradable emissions permits) will lower the demand for fossil fuels there – and thus also emissions will fall. This, however, also lowers the world market price for fossil fuels; and that in turn will increase the demand for fossil fuels in the non-policy region, leading to higher emissions there – thus the policy results in what is termed carbon leakage through the energy market leakage channel (or "fossil fuel price channel"). [12] Taken together, we observe two counteracting effects in energy markets: a drop in fossil fuel use and emissions in the region subject to the policy, and an increase in fossil fuel use and emissions elsewhere.

In non-energy markets the policy works as follows: carbon pricing imposes additional costs on the production of goods and services, making these goods and services more expensive. This, firstly, provides an incentive to producers to employ a less carbon-intensive production technology. Secondly, consumers (or buyers of intermediate products) will demand less of the now more expensive products. Both effects lead to a reduction of emissions. On the other hand, the policy also provides incentives to substitute the now relatively cheaper goods produced in the non-policy region for the expensive ones produced in the policy region. This effect causes an increase in emission – carbon leakage through the non-energy market leakage channel (or: "competitiveness channel", "production cost channel", "trade channel"). In the short term, only trade flows will change; in the long run, however also investment patterns may shift: while plants in the policy region might close down, new factories in the non-policy region might be built. Taken together, we again see two counteracting effects: on the one hand, the mitigation policy leads to a drop in the production and consumption of goods subject to the policy, and also to a "greening" of the production technology of these goods; on the other hand, production and consumption of goods not subject to the policy will increase. [13]

Both climate policy transmission channels are intertwined, and as we will see in section 5 and 6, their effects overlap. Still, we will discuss them one after the other, starting in section 5 with the non-energy market channel.

4 Partial equilibrium climate policy model

This paper aims to shed light especially onto two aspects of unilateral mitigation policy that have so far only seldom been examined by means of small analytical models: (i) changes in production technology triggered by the policy (modeled as changes of the mix of inputs into production); and (ii) the interrelationship between the energy-market and the non-energy market policy transmission channels. Representing these aspects in an analytical model introduces additional complexity as compared to some of the models discussed in section 2. To keep our model nonetheless analytically tractable, we will therefore confine our analysis to a partial equilibrium setting. This, of course, means that our analysis neglects some general

[12] See e.g. Droege, 2009, or Quirion, 2010, for an introduction to the different leakage channels.

[13] The non-energy market and the energy market channel as introduced here are not the only mechanisms for carbon leakage discussed in the relevant literature: Quirion (2010), for example, analyzes a second effect in energy markets, which he terms the "international cleaner goods channel". It works as follows: climate policy also raises the prices of "green goods" (e.g. bio-fuels) and thus also causes leakage. Additionally, climate policy changes the international income distribution, and that in turn might also have an effect on the amount of leakage. Burniaux and Oliveira Martins (2011) as well as Gerlagh and Kuik (2007) however argue that this effect will be rather small. Finally, a strict mitigation policy might induce the development of "green technology" in the policy region, which then might spill over to the non-policy region and cause "negative leakage" there. Gerlagh and Kuik argue that this effect might even dominate leakage through all the other channels. Still, not much is known about the possible size of this effect. Here, we will concentrate on the two channels that are better documented in the leakage literature.

equilibriums effects such as those pointed out by Houser et al. (2008) or Jakob and Marschinski (2012). Still, partial equilibrium analysis can contribute to our understanding of the impacts of a switch of the policy base in at least two ways: either (a) we are mainly interested in sector-specific effects (like e.g. Fischer and Fox, 2012), or (b) we see partial equilibrium analysis merely as a first step in the examination of the economy-wide effects of unilateral climate policy,[14] which can be complemented with general equilibrium analysis at a later stage. In this case, we should keep in mind that even though our model can be expected to reveal many of the more salient relationships characterizing consumption-based policy approaches, it will not reveal all such relationships. In the course of the following discussion, we will make use of interpretations (a) as well as (b).

Our model employs the two-region framework introduced in section 3. Again, to keep the analysis as simple as possible, no intermediate but only final goods are manufactured and traded. The structure of our model is inspired by the Fischer-and-Fox (2012) model discussed in section 2. Many features of that model have, however, been adapted and supplemented to permit an analysis of changes in technology induced by climate policy and to include the global fossil fuel market. Especially, in contrast to most of the models discussed in section 2, we will (however, in a fairly general fashion) parameterize our production and demand functions. All in all, five markets will be represented: in addition to the global market for (one aggregate type of) fossil fuel there are two final goods markets in each of the two regions. We start our discussion by describing supply and demand in these final goods markets.

4.1 Production

Home produces goods that can either be consumed domestically (in that case they are denoted by H as in section 3) or exported (in that case they are denoted by X). We assume that from the viewpoint of the consumer H and X are identical. To be able to study the effects of differences in the stringency of the mitigation policy for goods produced for the domestic market and those produced for export (e.g. an unequal taxation of these goods), we however allow for H and X to be produced with different technologies. More precisely, the form of the production function will be the same for H and X; but the input mix (i.e. the point chosen on this production function) may differ. We thereby diverge from the common assumption that goods sharing the same characteristics are always produced with an identical input mix. In this way our model gives producers the possibility to react rationally to unequal taxation;[15] and that, in turn, is essential to investigate in which way taxation can help to make the production technology employed more environmentally friendly. In the following, we will distinguish between "good H" and "good X"; we should however keep in mind that the difference between these two goods only relates to the market were they are sold (Home or Foreign) and possibly to the input mix used in their production, but not to their characteristics.

Technology in region Home is characterized by a constant-elasticity-of-substitution (CES) production function with constant returns to scale. One can think of this production function either as literally representing just one technology with smooth input substitution

[14] In a similar vein, Gros (2009) employs a one-good partial equilibrium model to derive the welfare consequences of the introduction of a carbon import tariff.

[15] As a practical example, think of a producer who uses old factories (employing "dirty" technology) to produce for the export market, but new factories (employing "clean" technology) for producing for the home market, when confronted with a policy that taxes emissions from production for *domestic* consumption only.

possibilities or – probably more realistically – as a smooth approximation of a set of distinct technologies using different input combinations. Either way, this CES technology will be employed to produce both H and X. The inputs into production are fossil fuel (quantity E_H for good H and E_X for good X) as well as a second input K (which can be thought of as a composite of all other inputs required for production). As discussed above, the input mix in the production of H and X may differ; we therefore need to specify the production function for each of the two goods separately:

$$H(E_H, K_H) = \gamma_1[\alpha_1 {E_H}^{\rho_1} + (1-\alpha_1){K_H}^{\rho_1}]^{\frac{1}{\rho_1}} \text{ and}$$

$$X(E_X, K_X) = \gamma_1[\alpha_1 {E_X}^{\rho_1} + (1-\alpha_1){K_X}^{\rho_1}]^{\frac{1}{\rho_1}}, \tag{4.1}$$

$$\text{where } \rho_1 = \frac{\sigma_1 - 1}{\sigma_1}.$$

Both production functions are standard CES functions: $\gamma_1 > 0$ is an efficiency parameter, $0 < \alpha_1 < 1$ is a distribution parameter, $\sigma_1 > 0$ is the elasticity of substitution, and ρ_1 is an auxiliary parameter determined by σ_1. One can interpret H and X either as the output of one economic sector (say, the steel industry or the cement industry), or, alternatively, one can see H and X as a stylized representation of the composite output of all sectors of the economy that use (a non-negligible amount of) fossil fuel as an input. We will come back to these two different interpretations when discussing the results of our analysis.

Next, consider the inputs into production and their prices: We assume that the price of input K, $p_K > 0$ is constant and focus our analysis on the effects of changes in the price of the other input, fossil fuel.[16] The market price of fossil fuel is p_E. Burning one physical unit of fossil fuel sets free one unit of CO_2 emissions. We assume that there are no other emissions generated in production (i.e. there are no process emissions); E_H and E_X therefore also give the overall amount of emissions discharged in production.

The government follows a climate policy by imposing a specific tax t on each unit of emissions. So t is what is usually referred to as the carbon price. But as emissions equal fuel input, t is also equivalent to an input tax on fossil fuel. For the producer the price of using one unit of fossil fuel thus equals the sum of the market price of fossil fuel and the tax, $p_E + t$. We will term $p_E + t$ the "gross price of fuel".

Depending on the input prices ($p_E + t$) and p_K, producers choose their optimal input mix. This optimal input choice is reflected in the unit cost functions (which can be derived from the production functions). If the tax on emissions is the same for goods H and X, the optimal

[16] The partial equilibrium assumption of constant prices for all factors (except fossil fuel) will typically be unproblematic if we study just a single economic sector. If we however interpret H and X to encompass all sectors using fossil fuel (and thus causing CO_2 emissions), these sectors will comprise a substantial share of the overall economy. Thus, the assumption that changes in the output of H and X will have no effect on factor prices will not hold in a strict sense. In that case, we should see partial equilibrium results only as an approximation to the relationships that characterize more complex models.

input mix in the production of both goods will also be the same; and therefore the unit costs c_H for H and c_X for X will be equal. The situation changes, if, for example, only emissions discharged in the production of good H are taxed, but not emissions in the production of good X. Then, the optimal input mix in the production of H and X and hence also the unit costs c_H and c_X will be different. In this case with unequal taxation, they are given by

$$c_H\left(p_E+t, p_{K,1}\right)=\frac{1}{\gamma_1}\left[\alpha_1{}^{\sigma_1}(p_E+t)^{1-\sigma_1}+(1-\alpha_1)^{\sigma_1}p_{K,1}{}^{1-\sigma_1}\right]^{\frac{1}{1-\sigma_1}} \text{ and}$$

$$c_X\left(p_E, p_{K,1}\right)=\frac{1}{\gamma_1}\left[\alpha_1{}^{\sigma_1}p_E{}^{1-\sigma_1}+(1-\alpha_1)^{\sigma_1}p_{K,1}{}^{1-\sigma_1}\right]^{\frac{1}{1-\sigma_1}} . \tag{4.2}$$

Region Foreign produces the goods F and M, also employing a CES technology with constant returns to scale in the production of both goods. The technology may, however, differ from the one used in Home; it is characterized by the parameters α_2, γ_2, ρ_2, and σ_2. Also, the input price $p_{K,2}$ may be different from $p_{K,1}$ (but the fuel price p_E is the same in both regions). The unit cost functions c_F and c_M can be derived in a similar way as in Home.

4.2 Emissions

From the cost functions, for of each of the goods the conditional input demand for fuel (which equals the "demand" for discharging carbon emissions) can be calculated. For good H it is given by

$$E_H=H\,\underbrace{\gamma_1{}^{\sigma_1-1}\left(\frac{\alpha_1 c_H}{p_E+t}\right)^{\sigma_1}}_{e_H}=He_H\,. \tag{4.3}$$

e_H is the emissions rate (the "physical counterpart" to the emissions intensity). Substituting for unit costs in (4.3) gives

$$E_H=H\,\alpha_1{}^{\sigma_1}\frac{1}{\gamma_1}(p_E+t)^{-\sigma_1}\left[\alpha_1{}^{\sigma_1}(p_E+t)^{1-\sigma_1}+(1-\alpha_1)^{\sigma_1}p_{K,1}{}^{1-\sigma_1}\right]^{\frac{\sigma_1}{1-\sigma_1}} . \tag{4.4}$$

For the other goods, the conditional demand for fuel can be calculated in a similar fashion. Global fuel demand E – and thus the global emissions linked to it – is given by the sum of the fuel demand for the production of the individual goods:

$$E=E_H+E_X+E_M+E_F=He_H+Xe_X+Me_M+Fe_F\,. \tag{4.5}$$

4.3 Demand and goods market equilibrium

Each region has a representative consumer. The representative consumer in Home demands goods *H* and *M*, the one in Foreign goods *X* and *F*. The demand for each of the four goods is a function of the price of the respective good and the price of the competing good in the same region. For example, demand *h* for good *H* is a function $h(p_H, p_M)$. p_H is the price of *H*, and p_M is the price of *M*. We assume constant elasticity of demand functions:

$$\begin{aligned}
h(p_H, p_M) &= \beta_h p_H^{\eta_{hH}} p_M^{\eta_{hM}}, \quad \text{with } \eta^{hH} = \frac{\partial h}{\partial p_H}\frac{p_H}{h} \text{ and } \eta^{hM} = \frac{\partial h}{\partial p_M}\frac{p_M}{h}, \\
m(p_H, p_M) &= \beta_m p_H^{\eta_{mH}} p_M^{\eta_{mM}}, \quad \text{with } \eta^{mH} = \frac{\partial m}{\partial p_H}\frac{p_H}{m} \text{ and } \eta^{mM} = \frac{\partial m}{\partial p_M}\frac{p_M}{m}, \\
x(p_X, p_F) &= \beta_x p_X^{\eta_{xX}} p_F^{\eta_{xF}}, \quad \text{with } \eta^{xX} = \frac{\partial x}{\partial p_X}\frac{p_X}{x} \text{ and } \eta^{xF} = \frac{\partial x}{\partial p_F}\frac{p_F}{x}, \\
f(p_X, p_F) &= \beta_f p_X^{\eta_{fX}} p_F^{\eta_{fF}}, \quad \text{with } \eta^{fX} = \frac{\partial f}{\partial p_X}\frac{p_X}{f} \text{ and } \eta^{fF} = \frac{\partial f}{\partial p_F}\frac{p_F}{f}.
\end{aligned} \tag{4.6}$$

The parameters β_h, β_m, β_x, and β_f are positive. Own-price elasticities are negative, while cross-price elasticities are positive. Thus, the competing goods in each region are gross substitutes.

In the market equilibrium, $H = h$, $M = m$, $X = x$, and $F = f$. Producers face perfect competition; prices will therefore equal the (constant) marginal costs of production, i.e. $p_H = c_H$, $p_M = c_M$, $p_X = c_X$, and $p_F = c_F$. Consider, for example, good *H*:

$$\begin{aligned}
H &= h(p_H, p_M) = \beta_h p_H^{\eta_{hH}} p_M^{\eta_{hM}} = \\
&= \beta_h \left(\frac{1}{\gamma_1}\right)^{\eta_{hH}} \left(\frac{1}{\gamma_2}\right)^{\eta_{hM}} \left[{\alpha_1}^{\sigma_1}(p_E + t)^{1-\sigma_1} + (1-\alpha_1)^{\sigma_1} {p_{K,1}}^{1-\sigma_1}\right]^{\frac{\eta_{hH}}{1-\sigma_1}} \\
&\quad \left[(\alpha_2)^{\sigma_2}(p_E + t)^{1-\sigma_2} + (1-\alpha_2)^{\sigma_2}\left(p_{K,2}\right)^{1-\sigma_2}\right]^{\frac{\eta_{hM}}{1-\sigma_2}}.
\end{aligned} \tag{4.7}$$

Supply and demand for the other goods can be derived in a similar way. By plugging (4.7) into (4.4) we can calculate fuel demand (and the emissions linked to it) for good *H*; and by substituting the result – and analogous results calculated for the other goods – into (4.5) we obtain world fuel demand. Thus, the structure of supply and demand relationships in the markets for the four final goods *H*, *X*, *M*, and *F* is as follows: The emissions tax and the fuel price determine emission rates and (unit) production costs. Production costs determine the goods prices. Demand then determines the quantities of the goods produced, and these, along with emissions rates, determine total fuel demand (and the emissions linked to it). The fifth market of our model, the global market for fossil fuel, will only be introduced in section 7.

5 Policy transmission in non-energy markets

To investigate the first of the transmission mechanisms for climate policy, the channel that works through price changes in non-energy markets, we assume that the market price for fossil fuel p_E remains fixed. As concerns carbon leakage, we thereby exclude energy market leakage effects. We will derive results on environmental effectiveness (i.e. the reduction of global emissions, see section 3) and carbon leakage of a consumption-based compared to a production-based policy for two policy scenarios: (a) the reduction of emissions directly targeted by the policy (i.e. emissions that are part of the policy-base) is the same for the two policies being compared; and (b) the carbon price for the two policies is the same. In the following, region Home will always be the policy region. It implements a climate policy by levying a carbon tax. Thus, the carbon price (the tax) is exogenous, and emissions will adjust endogenously.[17]

5.1 Policy effects for a single sector

First, consider the effects of the tax on the emissions discharged in the production of a single good, say good H. As the fuel price is fixed, we do not need to consider the supply side of the fuel market: fuel use and the emissions linked to it are given directly by the demand relationships (4.3) and (4.4). We will study the effects of the tax by means of comparative static derivatives. Starting from the equation $E_H = H e_H$, we obtain[18]

$$\frac{\partial E_H}{\partial t} = \frac{\partial H}{\partial t} e_H + H \frac{\partial e_H}{\partial t}. \tag{5.1}$$

As can be seen from 5.1, the tax affects emissions in two ways: first, demand for good H (and thus also supply) may change, and secondly, the emissions rate e_H in the production of H may change.

The effect on demand and supply can be calculated by differentiating 4.7 with respect to t. Assume for the moment that emissions both in the production of H and of the competing good M are taxed:

[17] Alternatively, one could model a cap-and-trade system, where emissions quantities are fixed and the carbon price adjusts endogenously. However, in order to keep the model as simple as possible, this alternative will not be pursued here.

[18] In this section, H, E_H, and e_H are functions of just one variable, t. We nonetheless use the symbol ∂ instead of d to denote the derivatives, as a second variable, p_E, will be introduced in section 6. For now, however, p_E, remains fixed.

$$\frac{\partial H}{\partial t} = H\left(\eta_{hH}\frac{e_H}{c_H} + \eta_{hM}\frac{e_M}{c_M}\right) = \frac{H}{p_E + t}\left(\underbrace{\eta_{hH}\theta_H}_{<0} + \underbrace{\eta_{hM}\theta_M}_{>0}\right),$$

$$\text{where} \quad \theta_H = \frac{e_H(p_E + t)}{c_H} = \frac{\partial c_H}{\partial(p_E + t)}\frac{(p_E + t)}{c_H} = \varepsilon_{p_H, p_E + t}, \tag{5.2}$$

$$\text{and} \quad \theta_M = \frac{e_M(p_E + t)}{c_M} = \frac{\partial c_M}{\partial(p_E + t)}\frac{(p_E + t)}{c_M} = \varepsilon_{p_M, p_E + t}.$$

To interpret 5.2, consider the expression following the second equality sign in the first line: θ_H is the share of gross fuel costs in overall input costs for *H*, and θ_M the share of gross fuel cost in overall input costs for *M*. As can be seen from the second and third line of 5.2, these cost shares however also give the gross fuel price elasticity of the output price of the respective good, i.e. they show the relative change in output prices caused by the relative change in the gross fuel price due to the introduction of the tax. To derive this result, differentiate 4.2 with respect to ($p_E + t$) and use the equality of unit costs and good prices. Both cost shares, of course, are positive. Now, consider the term $\theta_H \eta_{hH}$, the product of the gross fuel price elasticity of the price of *H* and the own-price elasticity of demand for *H*: it gives the relative change in demand for *H* triggered by the relative change in the gross fuel price via the change in the price of *H*. This product is negative as the own-price elasticity η_{hH} is negative. It represents one of the mechanisms that propagate the effect of the tax in our model: the tax raises the fuel price. This makes *H* more expensive, which in turn reduces demand for *H*.

A second propagation mechanism for the effect of the tax is represented by the term $\theta_M \eta_{hM}$, the product of the fuel price elasticity of the output price for good *M* and $\eta_{hM} > 0$, the cross-price elasticity of demand for *H*. This term is positive. It gives the relative change in demand for *H* triggered by the relative change in the gross fuel price via the change in the price of *M*, the good that competes in region Home with good *H*. The tax raises the fuel price, which makes *M* more expensive and thus shifts demand from *M* towards *H*.

Taken together, two effects opposing each other influence demand (and production) of *H*: one effect that works trough the own-price of *H*, and a second one that works through the price of the competing good *M*. Which effect dominates, and whether the tax causes the production of *H* to increase or to drop, depends on parameter values. If, however, only emissions discharged in the production of *H* (but not those in the production of *M*) are taxed, the tax unambiguously reduces demand for *H*.

Next, consider the effect of the tax on the emissions rate e_H. Differentiating the expression for e_H in 4.4 with respect to *t* gives

$$\frac{\partial e_H}{\partial t} = e_H \sigma_1 \frac{e_H(p_E + t) - c_H}{c_H(p_E + t)} = -\frac{e_H}{p_E + t}\sigma_1(1 - \theta_H)\,,$$

$$\text{with } -\sigma_1(1 - \theta_H) = \frac{\partial e_H}{\partial(p_E + t)}\frac{(p_E + t)}{e_H} = \varepsilon_{e_H, p_E + t}\,. \tag{5.3}$$

As one would expect, the whole expression $\partial e_H / \partial t$ is negative – an increase in the tax will cause the emissions rate to fall: production becomes less carbon intensive, as producers substitute the non-taxed input K for the taxed input fossil fuel. As can be seen by differentiating the expression for e_H in 4.4 with respect to $(p_E + t)$, the term $-\sigma_1 (1 - \theta_H)$ represents the gross fuel price elasticity of the emissions rate. Thus, this elasticity depends on the elasticity of input substitution σ_1 and on $(1 - \theta_H)$, the cost share of input K.

Finally, plugging both 5.2 and 5.3 into 5.1 gives the combined effect of the tax on emissions – through both changes in demand for H and changes in the emissions rate e_H:[19]

$$\frac{\partial E_H}{\partial t} = \frac{E_H}{p_E + t}\left[\underbrace{\eta_{hH}\theta_H}_{<0} + \underbrace{\eta_{hM}\theta_M}_{>0} \underbrace{-\sigma_1(1 - \theta_H)}_{<0}\right]. \tag{5.4}$$

Again, the own-price effect on demand for H and the effect on the emissions intensity lower emissions, while the cross-price effect on demand for H increases emissions. The overall effect may be positive or negative, depending on actual parameter values. If, however, emissions in the production of the competing good M are not taxed, then the tax definitely helps to lower emission in the production of H.

In a similar fashion, the effects of taxing the other final goods X, M, and F can be obtained. From 4.5, the impact of the tax on global emissions is given by

$$\frac{\partial E}{\partial t} = \frac{\partial E_H}{\partial t} + \frac{\partial E_X}{\partial t} + \frac{\partial E_M}{\partial t} + \frac{\partial E_F}{\partial t}\,. \tag{5.5}$$

5.2 Production-based policy

We can now compare a production-based to a consumption-based approach. Let us look at the production-based policy first. This policy taxes energy use in the production of H and X at an equal rate. The production costs and thus the prices of both H and X will therefore rise equally; and their emissions rates will fall equally. In Foreign, production costs and thus prices and emissions rates are unaffected by the policy and will therefore remain unchanged. The impact of the policy on global emissions can be obtained using 5.4 (and similar equations for the other three goods) and 5.5:

[19] See Allen (1938) for a similar derivation of the effect of price changes on input demand.

$$\frac{\partial E}{\partial t^{PB}} = \frac{1}{p_E + t^{PB}} \left\{ \underbrace{E_H[\eta_{hH}\theta_H - \sigma_1(1-\theta_H)]}_{<0} + \underbrace{E_X[\eta_{xX}\theta_H - \sigma_1(1-\theta_H)]}_{<0} + \right.$$

$$\left. + \underbrace{E_M\eta_{mH}\theta_H}_{>0} + \underbrace{E_F\eta_{fX}\theta_H}_{>0} \right\}. \qquad (5.6)$$

The superscript *PB* of the variable *t* signifies that production is the policy base. The input cost shares θ_H and θ_X are the same; to simplify we have therefore substituted θ_H for θ_X in 5.6.

As emissions in the production of *M* and *F* are not taxed, there is no cross-price effect on demand for *H* and *X*; emissions discharged in the policy region are therefore unambiguously reduced. This can be seen in equation 5.6 from the first two terms inside the curly braces. The policy thus works by lowering the emission rates in the production of *H* and *X* and by curbing demand for *H* and *X*. The third and the fourth term inside the curly braces, however, show that there is a cross price-effect on demand for *M* and *F*: As the prices of both *H* and *X* rise, consumers in Home as well as in Foreign substitute towards Foreign's production. Thus, emissions in the non-policy region rise – the third and the fourth term in 5.6 represent what we have defined as absolute leakage in section 3. Whether absolute leakage is larger or smaller than the emissions reduction in the policy region – and thus whether the policy helps to reduce global emissions or actually increases them – , depends on the actual parameter values of the model. There is nothing inherent in this model to prevent the leakage ratio from exceeding 100 percent.

As can be seen from equation 5.6, the magnitude of absolute leakage (through the non-energy market channel) is positively related to the following parameters and variables:

- The emissions associated with foreign production, E_M and E_F. These depend – as can be seen from 4.3 – on the production volumes *M* and *F* as well as on the emissions rates e_M and e_F (which are equal).
- The cost share of fossil fuel in domestic production, θ_H. As shown above, this cost share equals the gross fuel price elasticity of the output prices. θ_H depends on the technology of production and the level of the fuel price p_E relative to the price of the other input p_K.
- The cross-price elasticities η_{mH} and η_{fX} (i.e. the ease of substituting imports for domestic goods in Home and foreign produced goods for exports in Foreign).
- The level of the fuel price p_E (as compared to the level of the carbon price *t*).

The leakage ratio can be calculated by dividing the third and fourth term in 5.6 (representing absolute leakage) by the first and second term (see equation 3.6). Compared to absolute leakage, the leakage ratio thus depends on additional variables and parameters that determine the effectiveness of the climate policy in the policy region.

5.3 Consumption-based policy

Next, we introduce a mitigation policy in Home that uses consumption as the policy base. The tax will be levied on the carbon content of goods *H* and *M*. Note that it is irrelevant where the tax is collected: from the producer, from the consumer, or at the border. As the prices in our model are flexible, the tax burden will be passed on in each of these three cases in exactly the same way. What counts is that the tax base is different from the one of a production-based policy.

The imposition of the tax will cause an increase of the prices of the taxed goods, p_H and p_M, and a decline of the emission rates in the production of these goods, e_H and e_M.[20] The other goods prices, p_X and p_F, and their emissions rates e_X and e_F remain unchanged. The impact of this consumption-based policy (identified by superscript *CB*) on global emissions is given by

$$\frac{\partial E}{\partial t^{CB}} = \frac{1}{p_E + t^{CB}} \Bigg\{ E_H \Bigg[\underbrace{\eta_{hH}\theta_H}_{<0} + \underbrace{\eta_{hM}\theta_M}_{>0} \underbrace{-\sigma_1(1-\theta_H)}_{<0} \Bigg] + E_M \Bigg[\underbrace{\eta_{mH}\theta_H}_{>0} + \underbrace{\eta_{mM}\theta_M}_{<0} \underbrace{-\sigma_2(1-\theta_M)}_{<0} \Bigg] \Bigg\}. \tag{5.7}$$

Again, some of the effects of the policy reduce, while others – the cross-price-effects – raise global emissions. Still, using the substitution matrix of the representative consumer of region Home, one can show that the overall impact of the tax on emissions is always negative, i.e. global emissions will fall (see the annex to this article for a proof). This contrasts with a policy with production as its base, which – as we have seen – may involve leakage ratios of more than 100 percent and thus an increase in global emissions.

From equation 5.7 we can also see that all effects of the policy pertain to emissions in the production of *H* and *M*, i.e. to the emissions directly targeted by the policy. The emissions associated with the production of *X* and *F*, on the other hand, are not affected. Thus there is no carbon leakage (in the sense of an unintended effect outside the policy-base counteracting the effect in the policy-base, see equations 3.7 and 3.8). It is true that the taxed goods are produced in both Home and Foreign, and that therefore emissions measured according to the region's production will also change in Foreign. But here this is not considered leakage, as the policy studied does not focus on production, but on consumption, and we therefore have to apply a "consumption policy base" instead of a "production policy base". Thus, we can state a first central result of our analysis: *While carbon leakage through the non-energy market transmission channel is positive under a policy with production as its base, it is zero under a policy with consumption as its base.*

[20] Here our model diverges from the standard approach as followed for example by Fischer and Fox (2012): We permit that the climate policy pursued by Home influences production technology and thus the emissions rate e_M in Foreign.

At first glance, the result that there is no carbon leakage when consumption is the policy base might seem surprising. Should not producers faced with a consumption-based policy try to avoid the tax by concentrating their sales in the low-tax market, i.e. produce more exports and less for the domestic market in Home and vice versa in Foreign, a behavior that would raise emissions outside the policy base, i.e. cause leakage? While it is easy to conceive of such a reaction of producers in a real-world setting, our model does not exhibit such a behavior. This is due to one of the central assumptions of the model, the assumption of constant returns to scale in production (which results in the marginal cost curves being flat). Under this assumption producers can fully pass on any tax to consumers. Unlike consumers, who adjust their demand to avoid the tax, producers have no profit motive to shift production according to the policy applied. Thus, leakage in this model is caused by consumer preferences, but not by production technology.

Consumers, however, only under a production-based policy have the choice between one product that is affected by the policy and one that is not: for consumers in Home, emissions in the production of good H are taxed, but not those embodied in good M; and for consumers in Foreign, emissions embodied in good X are taxed, but not those in good F. If this policy is introduced, consumers will therefore increase their demand of a good that is not part of the policy-base; and that constitutes carbon leakage. A consumption-based policy, on the other hand, adds carbon costs to all products demanded by consumers in Home (and does not affect consumers in Foreign at all). Therefore, consumers in Home have no possibility to shift their demand to products not targeted by the policy. Their tax avoidance strategy will only involve substituting between the product with the larger tax burden and the product with the smaller one. But as there is no product that is not taxed at all (that is outside the policy base) in the consumption bundle of consumers in Home, there is no carbon leakage.

As we have seen, the zero-leakage property of a consumption-based policy rests on some of the assumptions of our model: on the one hand, the economic sectors of the model must exhibit flat market supply curves, on the other hand, both regions must enjoy some monopoly power in international trade: the two goods demanded by each of the representative consumers in Home and in Foreign must not be perfect substitutes. But how realistic are these assumptions? Typically, constant returns to scale and therefore flat supply curves are assumed to characterize a competitive industry in long-run equilibrium. Of course, not all of the economic sectors prone to leakage can actually be classified as competitive (Monjon and Quirion 2009, Reinaud 2008). The assumption of some monopoly power in international trade, on the other hand, is quite typical for models employed in the leakage literature – in CGE models it is usually implemented by means of the Armington (1969) assumption. But ultimately, the question whether our assumptions are a reasonable approximation to real world industry structure can only be answered empirically. Still, our model highlights the following point: when choosing between a production- and a consumption-based policy it is essential to know whether carbon leakage is triggered only by consumer or also by producer behavior.[21]

[21] Additionally also note that in a general as opposed to a partial equilibrium setting market supply curves will never be completely flat if the industry examined comprises of a non-negligible share of the overall economy. This is due to the fact that in a general equilibrium setting the supply of factors of production is fixed, and thus an industry that increases its factor demand drives up factor prices, which in turn raises (marginal) production costs.

5.4 *Policy evaluation in terms of environmental effectiveness*

The zero-leakage property of the consumption-based policy immediately implies the following result: *If we compare two policies that achieve an equal reduction of the emissions directly targeted by the policy* (i.e. the emissions that constitute the policy base – scenario (a) from the first paragraph of section 5), *the consumption-based policy is environmentally more effective* (see section 3 for the background to this result). This result, however, does not mean that this policy will always be the more cost-effective option (see section 5.6 for a discussion of cost-effectiveness). Also note that to achieve an equal reduction of the emissions of the policy base one must in general adopt different tax rates (i.e. impose different carbon prices) for the two policies being compared. If one instead compares two policies with equal tax rates (i.e. the same carbon price, scenario (b) from the first paragraph of section 5), we cannot immediately infer that the consumption-based policy will be the more environmentally effective one.

In the following, we will look at such a comparison of policies with the same tax rate in more detail. The difference in global emissions reduction between a production- and a consumption-based policy is in this case given by

$$\frac{\partial E}{\partial t^{PB}} - \frac{\partial E}{\partial t^{CB}} = \frac{1}{p_E + t}\left\{ \underbrace{-E_H \eta_{hM} \theta_M}_{<0} + \underbrace{E_X[\eta_{xX}\theta_H - \sigma_1(1-\theta_H)]}_{<0} \right.$$
$$\left. \underbrace{-E_M[\eta_{mM}\theta_M - \sigma_2(1-\theta_M)]}_{>0} + \underbrace{E_F \eta_{fX} \theta_H}_{>0} \right\}. \tag{5.8}$$

If the consumption-based policy is environmentally more effective, the whole expression will be positive. For this to be the case, the first two terms inside the curly braces must be small in absolute value and the third and fourth term must be large. The first term represents the cross-price effect on demand for good *H* under the consumption-based policy. This term shows that a consumption-based policy is less effective in reducing emissions in the production of good *H* than a production-based one, as the tax on emissions embodied in good *M* under the consumption-based policy leads to increased demand for good *H*. The second term represents the reduction in emissions of Home's exports *X* under the production-based policy. It is large in absolute value if either the amount of emissions embodied in exports, E_X, is itself large, or if E_X reacts strongly to the policy – in this case the term in brackets is large. The third term represents the reduction in emissions in Home's imports *M* under the consumption-based policy. Again, it is large if either the amount of emissions embodied in imports, E_M, is itself large, or if E_M reacts strongly to the policy. Finally, the fourth term represents leakage under the production-based policy (the other leakage term from 5.6, the one relating to E_M, cancels).

Taken together, little can be said on the question which policy is more effective without knowing the magnitudes of all the relevant parameters and variables: the amounts of emissions embodied in trade and in non-traded goods, the cost shares of fossil fuel, the elasticities of demand, and the elasticity of substitution between inputs in production. However, a few points warrant a more detailed discussion:

- *The magnitude of carbon leakage under a production-based policy is just one of a number of factors that decide whether a consumption-based policy* (with the same tax rate as the production-based policy) *is indeed environmentally more effective*. The other factors relate to the effectiveness of the policies in curbing the emissions that are included within the policy base. Thus, when choosing among different policies, one should not rely exclusively on the criterion of "minimum leakage".

- In many empirically relevant situations, E_H, the amount of emissions embodied in domestically produced goods consumed domestically will be larger than either E_M or E_X (at least, if the coalition following the climate policy consists not just of a single small country). As can be seen from the first term inside the curly braces in 5.8, *a consumption-based policy will however be less effective in reducing emissions in the production of H* than a production-based one. This by itself, however, should not be an argument for preferring the production-based policy: the reason why the production-based policy is more effective in reducing E_H is that consumers in Home have the possibility to evade the policy by switching to the non-taxed import good *M*, whereby they cause leakage. Under the consumption-based policy, on the other hand, the cross-price effect on demand for *H* (the first term in 5.8) prevents such an easy evasion of the policy. In that way, it however also diminishes the effect of the policy on emissions in the production of *H*.

- Peters and Hertwich (2008b) advocate a consumption-based policy on the grounds that – with current trade flows and emissions intensities – it includes a larger share of global emissions than a production-based policy. In terms of the model employed in this article, this means that E_M is larger than E_X. This without doubt is one of the most convincing arguments in favor of a consumption-based policy. Nonetheless, by itself this argument cannot guarantee that a consumption-based policy is always environmentally more effective. In particular, for the third term in 5.8 to be larger than the second term in absolute value, also the part of the third term in brackets needs to be sufficiently large, i.e. imports need to react sufficiently strong to the policy. And that in turn does not only depend on the emission rate in the production of imports (which is reflected in the input cost share θ_M), but also on the elasticity of demand for imports, η_{mM}, and on the elasticity of substitution in region Foreign, σ_2. Thus, *the fact that emissions in imports exceed emissions in exports in quantity does not automatically imply that targeting emissions in imports will lead to a larger reduction in global emissions than targeting emissions in exports.* Again, the magnitude of the parameters characterizing demand and production technology matters.

- Expanding on the argument in the previous paragraph, the attractiveness of a consumption-based policy rests – apart from its potential to avoid leakage – mainly on its effectiveness in reducing emissions in imports. As argued in section 1, in many industrialized countries these emissions have been growing extraordinarily quickly in recent decades. From the third term in 5.8 one can see that there are two ways to lower emissions embodied in imports: either the demand for imports is reduced – this option is represented by the term $\eta_{mM}\,\theta_M$ – or emissions in the production of imports are cut – this option is represented by the term $-\sigma_2\,(1-\theta_M)$. The first option is, of course, strongly opposed by developing and emerging economies (see e.g. Voituriez and

Wang 2011). It might also cause general equilibrium effects that actually diminish the effectiveness of the policy (see e.g. Jakob and Marschinski 2012). Steininger et al. (2012) argue that any politically feasible consumption-based policy followed by industrialized countries must therefore rely not on the first, but on the second option, i.e. it should aim not to reduce, but to "green" the export goods produced in developing countries. But whether taxing the emissions embodied in imports from developing and emerging economies indeed helps to "green" these imports, will be determined by the elasticity of substitution σ_2, or – stated in more practical terms – by the ease with which developing countries can switch production technologies. Thus, *the environmental effectiveness of a consumption-based policy crucially depends on the extent to which developing and emerging economies have access to "green" technologies.*

To summarize, for a particular coalition of industrialized countries choosing between a production- and a consumption-based policy with the same carbon price, the consumption-based approach may be the environmentally more effective one if one of the following conditions holds: leakage under a production-based policy is large or emissions embodied in imports (by far) exceed emissions embodied in exports. Additionally, developing countries must have the capacity to easily implement a less carbon-intensive production technology. Note also that all results derived so far can be interpreted both as relating either to individual economic sectors of the two regions studied – interpretation (a) in the first paragraph of section 4 – or to the two regions as a whole – interpretation (b) from section 4.

5.5 Switching the policy base, but not the target base

To conclude our discussion of policy transmission in non-energy markets, consider the consequences of switching just the policy-base, but not the target-base, i.e. we will analyze the use of a consumption-based policy to reach a target stated in terms of emissions in production. This scenario might be of interest to a country that thinks about unilaterally switching to a consumption-based policy to improve policy effectiveness even though the current UNFCCC system of production based emissions reduction targets is not changed, and that wants to know how far the consumption-based policy will help to reach these production-based targets. This is also the scenario usually adopted in the literature on border carbon adjustments. As mentioned in section 1, much of this literature however discusses border adjustment as a means to avoid losses in competitiveness stemming from unilateral carbon pricing. Also, often the kind of border carbon adjustments analyzed do not constitute a full switch to a consumption-based policy as either not all goods are included within the policy base or the emission taxes are not tied to the true carbon content of the taxed products. Here, we are however not interested whether a switch of the policy base can help to protect the industry of the country introducing the policy. As in the other parts of this article, we concentrate on the various measures of policy effectiveness.

In contrast to the previous section where we studied the environmental effectiveness of the policy on a global level, we now however want to know to what extent a consumption-based policy reduces the emissions discharged in production solely in the country introducing the policy, i.e. the emissions in the production of H and X. From 5.7 and 5.8 we see that the policy does not reduce emissions in the production of X at all, and also in the reduction of emissions in the production of *H* it is less effective than a production-based policy (see the first term inside the curly braces in 5.8). Actually, with certain parameter values a consumption-based policy can effect not a reduction, but even an increase of emissions in the production of *H* – and therefore also in the production of *H* and *X* taken together. For this to be the case, the middle term in brackets in the first line of 5.7 must be larger than the first and the third term in absolute value. Then, the sum of all three terms inside the brackets is positive, which means that emissions in the production of *H* rise.

A typical situation that leads to such effects might look as follows: the emissions rate in Foreign is far larger than the one in Home. Thus, also the tax levied on imports from Foreign will be higher than the one on domestic products. In Home, domestic production and imports both become more expensive, but as the price increase of imports is far higher than the one of domestic production, consumers demand less imports and more domestically produced goods. Production of domestic goods increases; and the additional emissions from this additional production more than outweigh the emissions savings that occur because the tax induces firms to produce the domestic good with a lower emissions rate. Thus, emissions discharged in region Home rise. Such a scenario will not only make Home miss its production-based emissions reduction target, it might also result in Home being heavily criticized by other countries for not taking its due share in international mitigation efforts: Home has introduced a policy that allows its own industry to increase emissions while causing emissions reductions in the industry of other countries.

However, not only emissions reduction in production in region Home is smaller under a consumption-based than under a production-based policy, the same also holds true for carbon leakage. For a production-based mitigation target, leakage must be calculated by formulas 3.5 or 3.6. And – as can be seen from the third and the fourth term inside the curly braces in equation 5.8 – the increase in emissions in the production of good *M* and *F* is definitely lower for a consumption-based policy as compared to a production-based one: actually, typically it is not an increase, but a drop.[22] Thus – as is well known from the literature on border tax adjustments – a switch to a consumption-based policy helps in reducing leakage through the non-energy market transmission channel.

Summing up, *emissions reduction in the production of the region introducing the policy as well as carbon leakage (calculated for a production-based target) is smaller under a consumption- than under a production-based policy.* As we know from the previous section, we however cannot determine whether the combination of these two effects is positive or negative without knowing the values of all relevant parameters, i.e. we cannot decide whether the switch of the policy base increases or lowers global emissions.

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[22] Under a consumption-based policy, emissions in the production of *M* and *F* taken together will fall if emissions in the production of *M* fall (as the production of *F* is not affected by a consumption-based policy). From the properties of the substitution matrix of the representative consumer in Home we know (see the annex to this article) that either the emissions in the production of *H* or those in the production of *M* or those in the production of both goods must fall. But as we have assumed that the emissions rate in the production of *M* is (by far) larger than the one in the production of *H*, it will indeed typically be the emissions in the production of *M* that fall (although – depending on the actual values of the elasticities of demand – an increase of the emissions in the production of *M* cannot be excluded).

5.6 *Cost-effectiveness and distributional impacts*

Most economists see cost-effectiveness as the most attractive of the policy evaluation criteria discussed in section 3. In fact, the comparison of two policies with equal tax rates performed in section 5.4 can be interpreted as a very simple cost-effectiveness analysis. To see why, note that producers and consumers will choose their level of abatement such that in equilibrium the tax rate (or carbon price) will equal marginal abatement costs. In general, abatement costs measured on the level of a whole economy reflect the loss of surplus by consumers who are no longer willing to buy the goods that have become more expensive due to the tax and also the loss of producers who no longer find it profitable to produce these goods (Weyant and Hill 1999). In our model, producers do not make profits in equilibrium; therefore, all costs represent the losses of surplus by the representative consumers in the two regions of the model. Of course, marginal abatement costs are a very crude approximation to total or average abatement costs (Stern, 2007). Still, we will use them here as a simple indicator of the costs of the policy. As we compare two policies with equal tax rates, marginal abatement costs – and thus our simple indicators of the overall costs of the policies – are equal for both policies. Then, the policy that brings about the greater reduction in global emissions is the more cost-effective one. The (marginal) reductions in global emissions of the two policies have, however, already been examined in section 5.4. All results stated there for environmental effectiveness thus also hold for cost-effectiveness.

In order to attribute the global costs to the two regions, a few additional issues have to be considered: First, the carbon tax raises revenues. These are fully recycled to consumers and thus on the global level do not affect costs. For each region individually, the tax however matters if the tax burden is not borne by the same representative consumer that also receives the tax revenues. Second, there may be sectors that are not directly taxed but still experience a change in their consumer surplus. In our model, these are the sectors affected by changes of the prices of competing goods via cross-price elasticities of demand. These cross-price changes shift the demand curves of the respective sectors and thereby influence consumer surplus. Finally, we have to make the typical assumptions for welfare analysis in partial equilibrium, i.e. all prices except for p_H, p_X, p_M, and p_F are fixed, there are no income effects on demand for H, X, M, and F, and utility is linear all goods except for H, X, M, and F. We will denote costs by $\mathcal{C}$, and more specifically abatement costs by $\mathcal{C}^A$.

Consider first a single sector of the model, say the production and consumption of good H. The abatement costs $\mathcal{C}^A{}_H$ depend on the amount of emissions reduction $\mathcal{R}_H$. We again examine the change of costs for a change of the tax t by one (infinitesimal) unit:

$$\frac{\partial \mathcal{C}_H^A(\mathcal{R})}{\partial t} = \frac{\partial \mathcal{C}_H^A}{\partial \mathcal{R}_H}\frac{\partial \mathcal{R}_H}{\partial t} = -t\frac{\partial E_H}{\partial t}. \qquad (5.9)$$

To derive the expression following the second equality sign, we have used the equality of marginal abatement costs $\partial\mathcal{C}^A{}_H / \partial\mathcal{R}_H$ and the tax rate t as well as the equality of $\partial\mathcal{R}_H / \partial t$ and $-\partial E_H / \partial t$.

Next, consider the effect of a change in the tax rate t on the tax revenue $T_H = E_H(t)\, t$:

$$\frac{\partial T_H}{\partial t} = \frac{\partial E_H}{\partial t} t + E_H \,. \tag{5.10}$$

An increase of the tax rate by one unit on the one hand raises the tax revenue by the number of emissions units taxed, E_H. On the other hand, the increase of the tax rate causes a drop of emissions by $\partial E_H / \partial t$, which lowers the tax revenue by this amount times any previous tax t. For a sufficiently small tax t the overall effect of an increase of the tax on the tax revenue must be positive, but there exists a tax level from which onward a further increase in the tax level lowers the tax revenue.

For the abatement costs and tax revenues in the other three sectors of our model similar expressions can be derived. These can be combined to give the overall effect on costs of a change in the tax for the two representative consumers of the model. We start with a production-based policy and the representative consumer in region Home:

$$\frac{\partial C_1}{\partial t^{PB}} = \underbrace{- t^{PB} \frac{\partial E_H}{\partial t^{PB}}}_{> 0} \underbrace{- t^{PB} \frac{\partial E_M}{\partial t^{PB}}}_{< 0} \underbrace{- t^{PB} \frac{\partial E_X}{\partial t^{PB}} - E_X}_{> 0 \; for \; small \; t} \,. \tag{5.11}$$

The first term in 5.11 represents the abatement cost in sector *H*. The second term depicts a gain in consumer surplus through a cross-price effect in sector *M* – thus this is a gain through carbon leakage. The third and the fourth term represent revenue from the tax on emissions embodied in good *X*, the export good of region Home. This revenue is traditionally collected by the country producing the good, i.e. Home. The welfare burden of the tax is however passed on to the representative consumer in Foreign: good *X* becomes more expensive, the representative consumer in Foreign therefore looses consumer surplus. Thus, the representative consumer in Home receives the revenues of the tax on *X* without having to bear an equivalent tax burden – she receives a “transfer” from the representative consumer in foreign, and this transfer lowers the overall cost of the policy (the tax revenue is positive for not too large values of *t*). For sufficiently small values of *t* the “transfer” from Foreign may actually be larger than the abatement costs incurred in region Home; and the representative consumer in Home may even experience a gain and not a loss of welfare by the introduction of the abatement policy.

The representative consumer in region Foreign, on the other hand, must bear the abatement cost (represented by the first term following the first equality sign in 5.12) and the tax burden (represented by the second and third term) in sector *X*. The fourth term reflects a welfare gain due to leakage:

$$\frac{\partial C_2}{\partial t^{PB}} = - t^{PB} \frac{\partial E_X}{\partial t^{PB}} + t^{PB} \frac{\partial E_X}{\partial t^{PB}} + E_X - t^{PB} \frac{\partial E_F}{\partial t^{PB}} = E_X - t^{PB} \frac{\partial E_F}{\partial t^{PB}} \,. \tag{5.12}$$

For not too large values of *t*, Equation 5.12 is unambiguously positive.[23] Thus region Foreign is burdened with substantial costs by the pursuit of the climate policy, even though it is region Home, and not Foreign that introduces the policy.

The situation is different for a consumption-based policy:

$$\frac{\partial C_1}{\partial t^{CB}} = -\, t^{CB} \frac{\partial E_H}{\partial t^{CB}} - t^{CB} \frac{\partial E_M}{\partial t^{CB}} \;. \tag{5.13}$$

As can be seen from 5.13, all costs of the policy are borne by the representative consumer in Home – and none by the one in Foreign. This is due to the fact that only goods consumed by the representative consumer in Home are taxed, and that producers can pass on all costs to consumers.

If we again assume that Foreign consists of developing and emerging economies, these countries are better-off under a consumption-based policy in the setting of our model. If we drop the assumptions that it is possible to pass on all costs to consumers, the results on the split of costs under the two policies might however be reversed. Most CGE models, for example, come to the conclusion that a shift to a consumption-based policy actually reduces the welfare of developing and emerging economies – see e.g. Boehringer et al. (2012a) for a recent comparison of 12 such models. The assumptions about cost pass-through possibilities are thus essential for the distributional effects of a switch of the policy base. In any event, our model-based analysis shows that (i) not only the country that introduces the policy must bear the cost of this policy, and (ii) the share of costs shifted onward across borders might be substantial.

6 Policy transmission in energy markets

The fossil fuel market, the fifth market of our partial equilibrium model, is represented as simple as possible. There is just one type of fuel, which is used as an input in the production of all four final goods. Thus, we do not discuss any inter-fuel substitution effects, which are often exhibited by more complex computable equilibrium models (see Burniaux and Oliveira Martins, 2011; Boehringer et al., 2010 for recent examples). Again, our aim is to reveal the most basic mechanics of policy transmission. Note, however, that the following discussion must be interpreted to relate to the world as a whole and not just to individual economic sectors – the global fuel market can only be studied by including all sources of fuel demand worldwide. Thus we make use of interpretation (b) from the first paragraph of section 4.

6.1 The transmission mechanism

Let the supply of fossil fuel *R* (*R* like resource*)* be given by a constant-elasticity function:

[23] The sign of 5.12 can be determined as follows: the sum of the first and the fourth term after the first equality sign is positive – see the annex to this article for a proof. The third and the second term represent the (change in the) tax revenue, which – as argued above – is also positive for not too large values of *t*.

$$R = \delta {p_E}^{\eta_R}, \qquad \text{with } \eta_R = \frac{\partial R}{\partial p_E}\frac{p_E}{R}. \qquad (6.1)$$

$\eta_R > 0$ is the price elasticity of fuel supply, δ is a parameter > 0, and p_E is the fuel price, which is the same in both regions as fuel is freely traded.

Global demand for fuel E is the sum of the input demands of the four industries which produce the final goods H, X, M, and F. The emissions tax affects the fuel market via its impact on these input demands. Thus, it is impossible to study the effect of the tax on price and quantity of fuel used by examining the fuel market in isolation – one needs to know how the tax influences production of H, X, M, and F; this is the point, where policy transmission through non-energy and through energy markets overlaps. In our model, on the demand side for fuel, this overlap is actually complete: there is no additional fuel demand by households, and there are no process emissions in the model either – thus also all emissions stem from the fuel demand of the four industries. This fuel demand – and the effect of the tax on it – has already been studied in section 5. Now we add the supply side of the fuel market to the analysis. The fuel price, which has been fixed so far, will now be determined endogenously. We will thereby obtain the combined effects of policy transmission in both non-energy and in energy markets.

In fuel market equilibrium, fuel demand equals fuel supply. As can be seen from 6.1, fuel supply R depends only on p_E. Fuel demand E, on the other hand, depends on both p_E and t (see equations 4.3 to 4.5):

$$E(p_E, t) = R(p_E) \,. \qquad (6.2)$$

Taking the total differential of both sides, we have:

$$\frac{\partial E}{\partial p_E} dp_E + \frac{\partial E}{\partial t} dt = \frac{dR}{dp_E} dp_E \,. \qquad (6.3)$$

From 6.1 and 6.2 we obtain:

$$\frac{dR}{dp_E} = \frac{\eta_R E}{p_E}. \qquad (6.4)$$

Rearranging terms of 6.3 and plugging in 6.4 yields an expression that gives the effect of the tax on global emissions, i.e. the overall effect of the policy studied.

$$\frac{dE}{dt} = \frac{\partial E}{\partial t} \frac{1}{1 - \frac{\frac{\partial E}{\partial p_E}}{\frac{\partial R}{\partial p_E}}} = \frac{\partial E}{\partial t} \frac{1}{1 - \frac{1}{\eta_R} \underbrace{\frac{p_E}{E} \frac{\partial E}{\partial p_E}}_{\varepsilon_{E,p_E}}} . \tag{6.5}$$

On the right side of 6.5, $\partial E / \partial t$, the partial derivative of E with respect to t, gives the effect of the tax on global emissions for the case that dp_E equals zero, i.e. the pure effect of the non-energy market transmission channel. The overall effect of both channels can therefore also be expressed as follows:

$$\frac{dE}{dt} = \varphi \frac{\partial E}{\partial t} \quad \text{with} \quad \varphi = \frac{1}{1 - \frac{\varepsilon_{E,p_E}}{\eta_R}} . \tag{6.6}$$

Equation 6.6 shows that φ, the effect of the fossil fuel market on global emissions, works as a multiplicative factor on the effect from non-energy markets, $\partial E / \partial t$, in determining the overall effect of the policy, dE / dt. This factor φ depends on η_R, the price elasticity of fuel supply, and on $\varepsilon_{E,pE}$, the price elasticity of fuel demand (which at the same time is the "demand side" fuel price elasticity of emissions).

Consider now the individual variables and terms of equations 6.5 and 6.6: $\partial E / \partial t$, the effect of the tax through the non-energy market channel, is given by 5.6 for a production-based and by 5.7 for a consumption-based policy. As discussed in sections 5.2 and 5.3, for a consumption-based policy $\partial E / \partial t$ will always be negative, whereas for a production-based policy $\partial E / \partial t$ may be either negative or positive – a positive value signifies a leakage ratio of more than 100 percent. Next, $\partial E / \partial p_E$, the demand side reaction of emissions to fuel price changes, and the corresponding elasticity $\varepsilon_{E,pE} = (\partial E / \partial p_E)(p_E / E)$, can be obtained using 4.4, 4.5, and 4.7. The derivation is similar to the derivation of the effects of the tax, only now we need to partially differentiate with respect to p_E instead of t:

$$\begin{aligned} \varepsilon_{E,p_E} = \frac{\partial E}{\partial p_E} \frac{p_E}{E} = \frac{E_H}{E} [\eta_{hH}\theta_H + \eta_{hM}\theta_M - \sigma_H(1 - \theta_H)] + \\ + \frac{E_X}{E} [\eta_{xX}\theta_X + \eta_{xF}\theta_F - \sigma_H(1 - \theta_X)] + \\ + \frac{E_M}{E} [\eta_{mH}\theta_H + \eta_{mM}\theta_M - \sigma_F(1 - \theta_M)] + \\ + \frac{E_F}{E} [\eta_{fX}\theta_X + \eta_{fF}\theta_F - \sigma_F(1 - \theta_F)] . \end{aligned} \tag{6.7}$$

Note that in 6.7 the input cost shares θ_H, θ_M, and θ_X depend on the rate and type (production- or consumption-based) of any previous emissions tax that is already in place when we begin our analysis. If we, however, start our analysis from a situation without any tax, we can evaluate 6.7 at $t = 0$. Then θ_H equals θ_X, and θ_M equals θ_F; and 6.7 can be simplified accordingly.

The individual terms of 6.7 are similar to the terms of 5.6 and 5.7, the equations that describe the effect of the tax on emissions. This is due to the fact that the effect of a change in the fuel price on production costs is similar to the effect of a change in the tax (see equation 4.2). Therefore, also the propagation mechanism from changes of the fuel price to changes in global emissions is the same as for the tax: the carbon rates in production change, and the goods prices change leading to substitution effects.

As is the case with the equations giving the effects of the tax, also in 6.7 each line contains positive as well as negative terms. Intuitively, one would of course expect that overall the negative effects must be stronger: a higher fuel price should lead to less fuel being used. This is indeed true for our model. It can be proved using the substitution matrix of the representative consumer in Home and in Foreign (see the annex to this article).

Knowing the signs of the derivatives and elasticities in 6.5 and 6.6, we can determine whether the fuel market factor φ increases or decreases global emissions. As $\varepsilon_{E,pE} < 0$ and $1 / \eta_R > 0$, their product will be < 0. The denominator in 6.5 and 6.6 will therefore always be greater than one; and the fuel market factor will take a value greater than zero and smaller than one. Thus the sign of $\partial E / \partial t$ will determine whether the fuel price channel increases or decreases global emissions:

- If leakage through the non-energy market channel is less than 100 percent, the fossil fuel market channel will increase global emissions and thus counteract the emissions reduction induced by the introduction of the tax. Still, the overall change in emissions caused by the policy will never become positive.

To see why note that $\partial E / \partial t$ can only be negative (which means that the policy causes a reduction of global emissions), if leakage through the non-energy market channel is less than 100 percent. As φ is positive but smaller than one, by 6.6 dE / dt is negative but smaller in absolute value than $\partial E / \partial t$. Thus the fuel market channel increases global emissions (as compared to the situation with only the competitiveness channel). However, there is a limit to how far global emissions may rise by means of the fuel price effect: Even if $\partial E / \partial p_E$ approaches minus infinity, φ and thus dE / dt will only approach zero. In that case the policy has no effect on the level of global emissions - but it can never have a negative effect as long as leakage through the non-energy market channel is less than 100 percent. A situation where mitigation policy has no effect will, for example, occur, if the price elasticity fuel supply is extremely low – the global amount of fuel used (and thus the level of emissions) will then always be the same, no matter how high the fuel price is.

- If leakage through the non-energy market channel is more than 100 percent, the fossil fuel market channel will reduce global emissions. Still, the overall change in emissions caused by the policy will never become negative.

The logic runs along similar lines as given above for the opposite case. But the reason for the reduction in global emissions can also be grasped intuitively. Leakage of more than 100 percent through the non-energy market channel means that the policy has not caused a drop, but an increase in fuel use. Therefore, bringing in the fuel market channel by freeing up the price of fuel will allow the fuel price to rise; and that in turn will dampen fuel use and thus emissions.

Finally, from equations 6.5 and 6.6 one can also see the circumstances under which the fuel market channel will have no effect. These are:

- The initial policy has no effect on global emissions through the non-energy market channel ($\partial E / \partial t = 0$). This can either be the case if carbon intensities and demand do not change as a reaction to the introduction of the policy; or if leakage is 100 percent (i.e. the positive and the negative effects of the policy on global emissions cancel).
- The fuel price elasticity η_R is very high (to be precise: infinite). Then the introduction of the mitigation policy will not influence the fuel price.
- Fuel price changes are not transmitted to emissions changes ($\varepsilon_{E,pE} = 0$). This will be the case if carbon intensities and demand do not change as a reaction to fuel price changes.

6.2 Policy evaluation in terms of environmental effectiveness

To compare the overall effects of a production- to those of a consumption-based policy, consider equation 6.6: the overall policy effect is the product of the effect as transmitted through non-energy markets, $\partial E / \partial t$, and the fuel price factor φ. As discussed in section 5.4, the effect through non energy-markets – and thus, the term $\partial E / \partial t$ – may differ between the two policies. The fuel market factor φ however is the same under both policies: it depends only on the fuel price elasticities of supply and demand, η_R and $\varepsilon_{Ew,pE}$, and these are independent of the choice of policy base.[24] Thus, *differences in the effect of a policy on global emissions* (i.e. differences in dE / dt) *are triggered by differences in the effectiveness of policy transmission through the non-energy market channel, but not by differences in the effect of the fossil fuel market. The fuel market only works like a "multiplicative factor" on these initial differences.*

This result is also intuitively plausible: for the fuel market effect, the only relevant question is by how much the demand for fossil fuel has been reduced by the policy. But it is irrelevant, how and where it was reduced - be it in the production of export goods or goods for domestic use, be it in region Home or in region Foreign.

Note, however, that this equality of the fuel market effect between a production- and a consumption-based policy refers only to global emissions reduction (and thus environmental effectiveness) but does not carry over to carbon leakage. This is due to the fact that the fuel price mechanism affects both the policy and the non-policy region. In the non-policy region

[24] Note that in the study of the effects of the introduction (or change) of an emissions tax, the independence of the price elasticity of fuel demand, $\varepsilon_{E,pE}$, from the choice of policy base also holds if there already is an emissions tax in place. It is true that this previous emissions tax will determine the magnitude of $\varepsilon_{E,pE}$ by its effect on the input cost shares θ_H, θ_M, and θ_X – and this magnitude will in general be different for a production- and a consumption-based policy. For the analysis of an infinitesimal change of the emission tax, we however must take this value of $\varepsilon_{E,pE}$, which is predetermined by the previous tax, as given. And this given value enters the calculation of the fuel price factor φ in the same way, irrespective of whether the additionally introduced (infinitesimal) tax is production- or consumption-based.

the drop of the fuel price brought about by the abatement policy causes leakage, whereas in the policy region it renders the pursuit of the abatement policy more difficult: for a given emissions tax rate, the reduction of emissions will be smaller if we allow for the fuel price effect (i.e. if we do not fix the fuel price); or alternatively for a given emissions reduction target a higher tax rate will be required under a flexible fuel price. In general, the split of the fuel price effect into the part that affects the non-policy region and the part that affects the policy region will not be the same for a production- and a consumption-based policy. Thus, also leakage through the energy market-channel will not be the same for the two policies.

In the following, we will derive a condition for leakage through both channels to be smaller under a consumption- than under a production-based policy. As discussed in section 5.3, leakage through the non-energy market channel is zero under a consumption-based policy. It is therefore always smaller (or equal) to leakage under a production-based policy through the non-energy market channel. As just discussed, the results for leakage through the energy market channel are not as clear-cut. We start our derivation of the combined leakage effect of both policy transmission channels from the two formulas for the leakage ratio given in section 3, equation 3.6, defining l^{PB}, and equation 3.8, defining l^{CB}:

$$l^{CB} < l^{PB} \Rightarrow \frac{1-l^{CB}}{1-l^{PB}} > 1 \;\; (if\; l^{PB} < 1)\,. \qquad (6.8)$$

We will focus on the case where $l^{PB} < 1$, i.e. where the leakage ratio is less than 100 percent, as this case is the empirically more relevant one. Again, we will analyze an infinitesimal change of the tax. Substituting in 6.8 yields

$$\frac{1-l^{CB}}{1-l^{PB}} = \frac{\dfrac{dE^{CB}}{dE_H^{CB}+dE_M^{CB}}}{\dfrac{dE^{PB}}{dE_H^{PB}+dE_X^{PB}}} = \frac{\dfrac{\frac{dE}{dt^{CB}}}{\frac{dE_H}{dt^{CB}}+\frac{dE_M}{dt^{CB}}}}{\dfrac{\frac{dE}{dt^{PB}}}{\frac{dE_H}{dt^{PB}}+\frac{dE_X}{dt^{PB}}}} > 1\,. \qquad (6.9)$$

Taking the total differential of $E_H(t, p_E)$ and using 6.3, we obtain an expression for the effect of the tax on emissions discharged in the production of H. We first assume a production-based policy:

$$\frac{dE_H}{dt^{PB}} = \frac{\partial E_H}{\partial p_E}\frac{dp_E}{dt^{PB}} + \frac{\partial E_H}{\partial t^{PB}} \quad \text{with} \quad \frac{dp_E}{dt^{PB}} = \frac{\frac{dE}{dt^{PB}}}{\frac{dR}{dp_E} - \frac{\partial E}{\partial p_E}}\,. \qquad (6.10)$$

In a similar way, we can proceed to derive expressions for the goods M and X, and also expressions giving the effect of a consumption-based policy. Plugging all these expressions into 6.9, rearranging terms and simplifying, we obtain the following condition for the leakage ratio to be smaller under a consumption-based than under a production-based policy:

$$\frac{\partial E_M}{\partial t^{PB}} + \frac{\partial E_F}{\partial t^{PB}} + \frac{dp_E}{dt^{PB}} \left(\frac{\partial E_M}{\partial p_E} - \frac{\partial E_X}{\partial p_E} \right) > 0 \,. \tag{6.11}$$

The first two terms in 6.11 represent absolute leakage through the non-energy market channel. They are positive. The third term is the difference between the indirect effect of a production-based tax via the fuel price on imports and the indirect effect of a production-based tax via the fuel price on exports. This term may be positive or negative, depending on parameter values. Substituting the respective terms from 5.6, 6.7, and 6.10, we have

$$\begin{aligned} l^{CB} < l^{PB} \Leftrightarrow & \frac{1}{p_E + t^{PB}} \left\{ E_M \eta_{mH} \theta_H \; + \; E_F \eta_{fX} \theta_H \right\} \\ & + \frac{\partial E}{\partial t^{PB}} \frac{1}{\eta_R - \varepsilon_{E,p_E}} \left\{ \frac{E_M}{E} \left[\eta_{mH} \theta_H + \eta_{mM} \theta_M - \sigma_1 (1 - \theta_M) \right] \right. \\ & \left. - \frac{E_X}{E} \left[\eta_{xX} \theta_X + \eta_{xF} \theta_F - \sigma_2 (1 - \theta_X) \right] \right\} > 0 \,. \end{aligned} \tag{6.12}$$

Again, the first term in 6.12 is positive; it represents absolute leakage through the non-energy market channel. The second term (line two and three of 6.12), on the other hand, stems from the leakage effects of the policy in the energy market. As $\partial E \,/\, \partial t^{PB}$ is negative for a policy that results in leakage through the non-energy market channel of less than 100 percent, the whole factor of the second term is negative. The part of the second term inside the curly braces may however be either positive or negative. If it is negative, leakage through the energy market channel is larger under a production-based policy. Let us now assume the (probably more typical) case that an increase in the fuel price leads to a drop (and not: an increase) in emissions in the production of both good *M* and good *X*. Then, for leakage through the energy market channel to be larger under a production-based policy, the first of the two terms inside the curly braces must be larger in absolute value than the second one, i.e. the impact of a change in the fuel price must be stronger on E_M than on E_X.

If on the other hand the expression inside the curly braces in 6.12 is positive, then leakage through the energy market channel is larger under a consumption-based policy. Still, that does not necessarily imply that also overall leakage through both channels is larger under a consumption-based policy. For that to be case, additionally the second term also needs to be larger in absolute value than the first term in 6.12, which represents leakage through the non-energy market transmission channel. This case can, of course, not be excluded; it however requires a certain combination of parameter values. In general, as can be seen from equation 6.12, overall leakage through both channels is the smaller for a consumption-based policy as compared to a production-based policy, the larger is the effect of the non-energy market channel compared to the energy market effect and the larger is the amount of emissions embodied in imports, E_M, compared to emissions embodied in exports, E_X.

7 Conclusions

As the prospects for an international agreement on a globally coordinated GHG abatement strategy appear bleak, individual countries study unilateral approaches to mitigation as a second-best strategy. One such second-best option is a switch to a consumption-based policy orientation. It promises to extend the reach of unilateral climate policy beyond the borders of the country pursuing the policies, as it affects the export production of countries not participating in the policy. This paper has employed a small two-region, five-good analytical partial equilibrium model to study some of the basic economic mechanisms behind arguments used in favour or against such a policy switch. The criteria of environmental effectiveness, cost-effectiveness, carbon leakage were used to evaluate the effectiveness of the different policies. Also, impacts of the policy switch on the international distribution of income were briefly reviewed.

A first result relates to the widely-used criterion of (policy induced) carbon leakage. We argue that applying this criterion according to its standard definition is problematic when evaluating a consumption-based policy: in that situation, the leakage measure does not convey any information on the question whether the policy helps to reduce global emissions. We therefore suggest a different definition of carbon leakage for use with consumption-based policy approaches. Applying this definition, we find that carbon leakage through the non-energy market policy transmission channel is positive under a policy with production as its base, but it is zero under a policy with consumption as its base. This result is partly due to one of the characteristics of our model – the fact that producers can fully pass on the tax burden to consumers, or put in other words, that we investigate a long-run equilibrium where producers do not make any profits. This, of course, is a special case – still, it seems worthwhile to investigate to what extent this special case represents some real-world situations. If it does, the “no-leakage property” of consumption-based approaches is one of the central arguments that can be used in its favor.

More generally, we however argue that one should not exclusively rely on the criterion of carbon leakage when choosing among different policies. Leakage only assesses the effects of a policy outside the emissions base directly targeted by the policy. When evaluating policies one however also needs information of the effects of the policies on the emissions base directly targeted. As concerns the effects of a consumption-based compared to a production-based policy, the amount of leakage is just one of a number of terms that decide which of the two policies leads to a larger emissions reduction.

We therefore concentrate on the criteria of environmental effectiveness (i.e. the amount of reduction of global emissions) and cost-effectiveness when comparing policies with different policy bases. A switch to a consumption-based policy has sometimes been advocated on the grounds that – with current trade flows and emissions intensities – it includes a larger share of global emissions than a production-based policy. While this is a convincing argument, we show that by itself it cannot guarantee that a consumption-based policy is environmentally more effective or more cost-effective: it does not suffice to look at the levels of emissions included in the emissions base of the policies being compared; one also needs to examine how good the policy is in changing these levels. Thus, only an examination of parameters such as the cost shares of fossil fuel in production, the elasticity of substitution between inputs, and the price elasticities of demand will reveal whether a consumption-based approach is indeed environmentally more effective or more cost-effective.

A special focus of our analysis was the question whether a switch of the policy base might contribute to the adoption of an environmentally more friendly technology. Empirically, emerging economies currently employ a much more carbon-intensive production technology than industrialized countries. Consumption-based policies followed by industrialized countries, with their reach extending to the export production sector of emerging economies, promise to incentivize a "greening" of production in these export sectors and could thus significantly contribute to a reduction of global emissions. Whether that promise actually materialises, however, depends on a number of factors. Basically, abatement policies work through two channels: On the one hand, they curb the amount of carbon-intensive consumption and production (this is sometimes termed "scale-reduction"), and on the other hand, they trigger the adoption of a less carbon-intensive production technology. While many analytical climate-policy models investigate only scale-reduction, we have explicitly also modelled the option that producers change their production technology (represented as a change in the input mix). In actual real world climate politics, scale reduction is heavily opposed by emerging economies; a "greening" of the production technology might therefore be the only politically feasible way to reduce the emissions of these economies. For this to happen, emerging economies however (i) must have access to "green" technologies; and (ii) the carbon (border) tax must be designed such that producers are charged only for the actual amount of carbon embodied in their products – and not some industry average or a measure based on the best available technology, as is often suggested.[25] Otherwise, they have no incentive to change their technology. Note also that the only limited cost-gains of the introduction of carbon border adjustments shown by many simulation studies is in many cases due to the absence of exactly such abatement incentives to producers in emerging economies (Boehringer et al. 2012a). In practical terms, the design of a tax that provides the required incentives might prove challenging. Without such a tax and without the availability of "green" technology in emerging economies[26], however, one of the main advantages a consumption-based policy might have is lost.

We also examine the energy market channel of climate policy transmission. This channel – according to many simulation studies – may contribute more to carbon leakage than the non-energy market channel. We, however, find that – at least in the simplified setting of our model with just one type of fossil fuel – the energy market transmission channel does not decide whether a production- or a consumption-based policy is environmentally more effective. This is decided by differences in the effectiveness of policy transmission through the non-energy market channel – the fossil fuel market only works like a "multiplicative factor" on these initial differences in effectiveness.

[25] See Boehringer et al. (2012b) for a recent discussion of different border tariff design options and their respective effectiveness.
[26] See Steininger et al (2012) for a more detailed discussion of the argument that emerging economies must have access to "green" technology.

Finally, we find that a switch of the policy base may lead to a substantial redistribution of the costs of the policy. In our model, under the production-based policy costs are shared between the countries following the policy and those that do not; under the consumption-based policy costs are borne exclusively by the countries that pursue the policy. Thus, if it is industrialized countries that introduce the policy, developing and emerging economies would be better-off with a consumption-based policy. This result is due to our assumption that all costs of the policy can be passed on to consumers. Simulation models with different assumptions on possibilities for cost pass-through usually arrive at the opposite conclusions: a shift to a consumption-based policy reduces the welfare of developing and emerging economies. Whatever result applies in a specific situation, the important point is that a switch of the policy base has the potential to cause huge redistributions of the costs of the policy. In practical terms, the size and direction of these redistributions may often decide whether a switch of the policy base has any chance to be actually implemented or not.

Summarizing, there exist a number of arguments that make consumption-based approaches appear an attractive policy option, e.g. the large amount of emissions embodied in imports from emerging economies that could be brought into the scope of the policy; or the possibility that a consumption-based policy leads to less leakage in the sense of counteracting effects on emissions not directly targeted by the policy. Our model-based analysis, however, shows that none of these arguments per se suffices to make a consumption-based policy the environmentally more effective or the more cost-effective option. Whether it is indeed more effective depends on (i) demand and production parameters and (ii) the precise design of the border tax (or any other appropriate policy instrument). Additionally, a switch of the policy base potentially also causes a substantial redistribution of the costs of the policy between abating and non-abating countries.

Annex

In this annex we show that a consumption-based policy will always lead to a reduction (and not an increase) in global emissions through the non-energy market policy transmission channel. We start from equation 5.7. As can be seen, the policy affects emissions discharged in the production of goods H and M. Both goods are consumed by only one of the two representative consumers of our model, the representative consumer of region Home.

We will analyze the effect of the introduction of a positive tax. Our aim is to show that this will cause a drop in emissions in the production of H and M, i.e. that $\partial E / \partial t^{CB} < 0$. The two terms $-\sigma_1 (1 - \theta_H)$ and $-\sigma_2 (1 - \theta_M)$ in 5.7 will always be negative. It therefore suffices to show that the remainder of 5.7 (which we will denote by the letter V) cannot become positive. To this end, we first employ the Hicks-Slutsky equation in elasticity form to disaggregate the four price elasticities of demand in 5.7 into net substitution and income components:

$$V = \frac{E_H}{p_E + t^{CB}} \left[\theta_H \left(\frac{\partial H}{\partial p_H} \bigg|_{U=const.} \frac{p_H}{H} - H \frac{\partial H}{\partial I} \frac{p_H}{H} \right) + \right.$$

$$\left. + \theta_M \left(\frac{\partial H}{\partial p_M} \bigg|_{U=const.} \frac{p_M}{H} - M \frac{\partial H}{\partial I} \frac{p_M}{H} \right) \right] +$$

$$+ \frac{E_M}{p_E + t^{CB}} \left[\theta_H \left(\frac{\partial M}{\partial p_H} \bigg|_{U=const.} \frac{p_H}{M} - H \frac{\partial M}{\partial I} \frac{p_H}{M} \right) + \right. \tag{A.1}$$

$$\left. + \theta_M \left(\frac{\partial M}{\partial p_M} \bigg|_{U=const.} \frac{p_M}{M} - M \frac{\partial M}{\partial I} \frac{p_M}{M} \right) \right].$$

I denotes income (of the representative consumer). As both H and M are normal goods, the income components – the second terms in parentheses in each line – are all negative. Thus they also cause emissions to fall. If we are now able to show that the sum of the other four terms – the net substitution components – cannot become positive, V will definitely be smaller than zero. The net substitution components represent the elasticities of compensated demand (as opposed to the four original elasticities η_{hH}, η_{hM}, η_{mH}, and η_{mM}, which are calculated from non-compensated demand). We will now use two results that hold true for compensated demand, if a consumer's expenditure function is twice continuously differentiable: (a) the cross-substitution effects are symmetric: $\partial H / \partial p_M |_{u=const.} = \partial M / \partial p_H |_{u=const.}$; and (b) the substitution matrix $S = [\partial x_i / \partial p_j |_{u=const.}]$, i.e. the matrix formed from all substitution and cross-substitution terms, is negative semidefinite. From (b) we have:

$$\frac{\partial H}{\partial p_H}\bigg|_{U=const.} \frac{\partial M}{\partial p_M}\bigg|_{U=const.} - \frac{\partial H}{\partial p_M}\bigg|_{U=const.} \frac{\partial M}{\partial p_H}\bigg|_{U=const.} \geq 0\,. \tag{A.2}$$

A.2 can also be written in elasticity form. If we additionally multiply each elasticity by the factor of the respective elasticity in equation A.1, we arrive at a relationship between the changes in emissions caused by the net substitution terms:

$$\frac{E_H}{p_E + t^{CB}} \theta_H \left(\frac{\partial H}{\partial p_H} \bigg|_{U=const.} \frac{p_H}{H} \right) \frac{E_M}{p_E + t^{CB}} \theta_M \left(\frac{\partial M}{\partial p_M} \bigg|_{U=const.} \frac{p_M}{M} \right)$$

$$- \frac{E_H}{p_E + t^{CB}} \theta_M \left(\frac{\partial H}{\partial p_M} \bigg|_{U=const.} \frac{p_M}{H} \right) \frac{E_M}{p_E + t^{CB}} \theta_H \left(\frac{\partial M}{\partial p_H} \bigg|_{U=const.} \frac{p_H}{M} \right) \geq 0. \tag{A.3}$$

Now consider the two cross-elasticity terms (the second line of A.3). We will show that they are equal. By (a) we can substitute $\partial H / \partial p_M |_{u=const.}$ for $\partial M / \partial p_H |_{u=const.}$ in the second of the two terms. Using 4.3 and 5.2, we also substitute for E_H, E_M, θ_H, and θ_M:

$$\frac{e_H H}{p_E + t^{CB}} \frac{e_M(p_E + t^{CB})}{c_M} \frac{p_M}{H} \left(\frac{\partial H}{\partial p_M} \bigg|_{U=const.} \right) =$$

$$= \frac{e_M M}{p_E + t^{CB}} \frac{e_H(p_E + t^{CB})}{c_H} \frac{p_H}{M} \left(\frac{\partial H}{\partial p_M} \bigg|_{U=const.} \right). \tag{A.4}$$

As can be seen from A.4, the two cross-elasticity terms in A.3 are indeed equal. A.3 is therefore of the form $ab - c^2 \geq 0$. For $a, b < 0$ and $c > 0$, this however implies $|a + b| - 2c \geq 0$, and that is exactly what we wanted to show: The sum of the (negative) own-price net elasticity terms is larger or equal in absolute value than the sum of the (positive) cross-price net elasticity terms; the change in emissions triggered by all four net substitution terms taken together is therefore smaller or equal to zero. And as all the other terms in 5.7 and A.1 – the income effect terms as well as the terms $-\sigma_1 (1 - \theta_H)$ and $-\sigma_2 (1 - \theta_M)$, the gross fuel price elasticity of the emissions rate – are negative, the introduction of a positive tax indeed causes a drop in emissions in the production of *H* and *M*.

In a similar way one can also prove that $\partial E / \partial p_E$ and the elasticity $\varepsilon_{E,pE}$ are both strictly smaller than zero (see equation 6.7): Start by splitting the four goods of the model into two pairs: the pair of goods demanded by the representative consumer in region Home, *H* and *M*, and the pair of goods demanded by the representative consumer in Foreign, *X* and *F*. For each pair of goods one can then show separately that a rise of the fuel price leads to a drop in emissions. Thus, also the overall effect of an increase in the fuel price is a drop in emissions.

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