Economic effects of unilateral European climate action*

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Abstract

Unilateral climate policy by the EU can be detrimental for global climate protection. Our purpose is to provide an economic analysis of this policy, to quantify the risk of carbon leakage, and to investigate economic effects related to the potential anti-leakage policy measures. We analyze existing definitions of carbon leakage and propose a new rigorous one. This is then tested using computable general equilibrium analysis for unilateral carbon dioxide abatement programs in the European Union in 2020, adopted under the United Nations Framework Convention on Climate Change (8%, 20% and 30% emission reduction relative to 1990). Our model of the global economy is disaggregated into three regions (the EU, the rest of the Annex I and non-Annex I countries). The analysis includes a decomposition of change in carbon emission using Logarithmic Mean Divista Index. While some anti-leakage measures (such as border tax adjustment on imports) reduce carbon leakage significantly, some of them are less effective. We found that output-based allocation of free emission permits to energy-intensive and trade exposed sectors reduce the leakage rate slightly, and a clean development mechanism -- depending how it is defined -- can either remove or increase carbon leakage. The results crucially depend on technical assumptions adopted in such models. We identified a list of parameters (like intra-import and Armington elasticities) which affect not only the magnitude but also the sign of carbon leakage rate. Manipulating with elasticities of substitution in production function suggests that in reaction to the unilateral action of the EU, the other regions may both increase or decrease their carbon emissions. Even though we are positive about computable general equilibrium models' application in this policy area, their policy simulations cannot be directly treated as policy recommendations without a careful validation of their assumptions.

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1. Introduction

Economic impacts of mitigation strategies and regional burden-sharing have been the focus of many analyses of climate action (see Habla and Winkler 2011, Boehringer et al. 2011, Kuik and Hofkes 2010, McLure Jr. 2010, Mattoo et al. 2009). There have also been studies addressing climate impacts of policies adopted or contemplated by some regions (see Fischer and Fox 2010, Llavador et al. 2010, Reinaud 2008). In particular, there are analyses of unilateral reduction strategies adopted or to be adopted by the European Union (see Steininger et al. 2011, Schinko 2010, Loeschel et al. 2008). This paper provides a similar exercise, but with an important 'value added' which is briefly explained below. Namely we propose a new rigorous definition of carbon leakage, we provide a decomposition of the change in carbon emission into four effects (economic activity, economic structure, energy intensity, and energy mix), and we simulate a clean development mechanism in two ways. Our purpose is to provide an economic analysis of unilateral climate policy by the EU, quantify the risk of carbon leakage, and investigate economic effects related to the potential anti-leakage policy measures. Because of the increasingly integrated global economy, unilateral climate action has global economic effects and results in altered carbon[1] paths. If a climate action results in emission increases, a part of this additional emission is a carbon leakage that appears when greenhouse gas (GHG) emissions in some regions is triggered by GHG reductions in other regions. Our hypothesis is that the unilateral climate policy by the EU is ineffective and it may be even detrimental for global climate protection.

How many regions should be in an evidence-based analysis to inform policy makers and enhance chances for a more effective climate change agreement? Authors of publications mentioned above disaggregate the global economy into 10 regions on average, and not less than five regions. The more regions are included, the more complicated the analysis becomes and more assumptions are made. On the other hand, with few regions we are able to provide only very simple analysis. The simplest case could cover two regions according to the Berlin Mandate (1995) under the United Nations Framework Convention on Climate Change (UNFCC) that establish 'common but differentiated responsibilities'. The first group of countries (known as Annex I countries) is to take binding commitments, while the second group (so-called non-Annex I countries) does not take any. The major effect of the Berlin Mandate was the decision by the United States (an Annex I country) not to join the Kyoto Protocol (1997). Other countries from the Annex I (such as Canada, Russia, and Japan) indicated that they would not take up targets in the second commitment period (2013-2020), even though they signed up for the first commitment period (2008-2012). The EU, as the only one from the top 10 emitters, has signed up for the second commitment period and even tries to increase the target for itself unilaterally. It is clear that Annex I countries should be differentiated in analyses of climate protection strategies, but there is no need for differentiation of non-Annex I countries from this point of view.

Thus we propose a three-region model in order to provide a simulation analysis for 2020, with the EU kept separate from the rest of the Annex I countries. It is obvious that countries are not homogeneous within regions, nevertheless, our three-region analysis explains that an unilateral reduction policy is not as obvious and effective as some analysts believe. We use a static computable general equilibrium (CGE) model of the global economy based on 2004 data with a forward recalibration for 2020. The previous version of the model together with the recalibration mechanism was prepared by C.Boehringer and T.Rutherford for a study of transition towards a low carbon economy in Poland (World Bank 2011a). It includes 13 production sectors, a representative household and a government in each region. We

[1] We use the words 'carbon' and 'emissions' interchangeably as shorthand for greenhouse gas emissions, usually measured in carbon dioxide equivalent (CO_2e) units.

modified the original model, and updated the underlying major assumptions. Also, we corrected border tax adjustments and projected data, and implemented the Logarithmic Mean Divista Index for decomposition analyses of carbon emissions by region.

A major issue in many modeling exercises of carbon leakage is that they reflect authors' assumptions regarding actions that are expected on behalf of some agents whereas these actions crucially depend on agreements reached and instruments applied. We cannot assess the overall effect of a reduction of emissions from one country without further precisions on the way it is done. Our paper includes several scenarios which differ only in instruments, not in emission targets. We demonstrate that assumptions widely accepted in economic analyses – such as the Armington elasticity of substitution or elasticities of substitution in the nested production function – drive the results of models serving as a basis for policy inspiration. For example, Gerlagh and Kuik (2007) relate modeling results from the relevant literature to some elasticities using meta-analysis and OLS estimation in order to explain the relationship between parameter choice and carbon leakage. However, the authors overlook the fact that there may be other driving factors as well. For example, the carbon leakage results depend on which regions are defined as those that undertake an abatement program, and what is the baseline scenario which serves as a benchmark. If the baseline case assumes no reduction target, then the carbon leakage rate for a 20% reduction target will be smaller than the carbon leakage for the same 20% reduction target but calculated in relation to the climate policy, say, with a 5% emission target. Thus, caution is needed whenever the results are fed into policy-making processes.

Another area where modeling can strongly influence policies is scenario building. Frequently, scenarios rely on hypothetical actions which reflect analysts' expectations or convictions rather than realistic projections. A good example of an approach which stresses the need for achieving certain outcomes rather than studying what decisions are likely to solve the problem is provided by Van Vuuren et al. (2011) on the representative concentration pathways. In this vein, we analyze some questions regarding climate protection through a clean development mechanism (CDM) scenario. European legislation lets domestic firms comply with some requirements by offsets which are validated by external parties. Doubts are caused by the fact that reductions refer to baseline paths which are not binding for the host countries. Our simulation experiment with the CGE model includes two cases for the international carbon offsets, where the baseline emission level for non-Annex I countries is determined *before* and *after* the mechanism is implemented. Yet the rationale behind introducing CDM is lowering the abatement cost, it might help to reduce "leakage" via permit price. The first case, which is not applied when non-Annex I countries do not have binding emission ceilings, solves the problem with carbon leakage by definition, but in the second one we see a significant increase in carbon leakage. This calls for more work on the rationale of international carbon offsets.

The rest of the paper is organized as follows. Section 2 provides a theoretical concept of carbon leakage. We analyze two approaches to define the leakage concept and provide a comparison with the definitions applied in the literature. Section 3 analyzes anti-leakage measures. Section 4 discusses details of the modeling tool we applied in policy simulation and the policies affecting carbon leakage. In the next section, we decompose the global change in carbon emissions, and interpret the results of policy simulations. We compare the results using four alternative definitions of carbon leakage rate. Section 6 provides an analysis of critical parameters which determine the sign and the magnitude of carbon leakage rate. The last section summarizes the main conclusions from our analysis.

2. Carbon leakage

Carbon leakage (CL) is defined as an emission in one geographical area resulting from a decrease in emissions elsewhere, everything else being constant, including policies elsewhere. Theoretically it may happen that these policies elsewhere may change as a result of inspiration caused by the EU unilateral reduction policy; but we do not speculate on this. In our study, we follow the convention to measure CL in relative terms as a part of the targeted emission reduction. Obviously, this definition is difficult to be formalized. First of all, CL is always a function of an abatement program elsewhere. Let us assume that N denotes the region where the carbon emissions "leak to", though it may undertake some (relatively less ambitious) climate action, and A denotes the region which undertakes a more ambitious abatement program. One approach is to define CL as the difference between the expected emissions in region N if there is an abatement program in region A, and emissions in region N provided business-as-usual policies in region A:

$$CL(\Delta R) = (f_N(GDP_N, P_N, GDP_A(R_0+\Delta R)) - f_N(GDP_N, P_N, GDP_A(R_0))) / \Delta R \qquad (1)$$

or in terms of a partial derivative:

$$CL(\Delta R) = \partial f_N / \partial R \; | _{R=Ro}$$

where

R_0 is the baseline reduction target adopted in A,
ΔR is an additional reduction target contemplated in A,
P_N identifies an abatement policy adopted in N,
f_N is an emission function for N,
GDP_A is a function of a reduction target adopted in A.[2]

This definition of carbon leakage allows for any sign and any level of the indicator. CL(ΔR) can be either positive or negative. Negative values – emission reduction in N corresponding to an increased carbon abatement target adopted in A – may arise as a result of complex processes that take place in the world economy following an increased abatement effort in one region. For example, this occurs if the transition of A to a low-emission economy induces a strong technological progress which is then adopted in N. In such a case, increased global output could be accompanied with less pollution globally. Positive values – emission increase in N corresponding to an increased abatement target adopted in A – is a result of moving production to where it is not constrained by environmental standards.

In this definition it is crucial that, ceteris paribus, only R and GDP_A changes. However, it is very difficult to comply with this assumption since all variables are linked to each other. GDP in each region depends on reduction targets in several ways. First, increasing reduction targets is typically associated with a slowdown in GDP growth. Second, increasing reduction targets is expected to decrease global prices of fossil fuels; this is likely to increase the demand for fossil fuels in N and – consequently – to increase emissions in N. However, this effect is not observed in regions with binding commitments. Third, technological progress and economies of scale in low carbon technologies – expected as a result of

[2] GDP may not be implemented into the CL formula directly, but it represents an economic situation determined by a given scenario.

increased reduction targets in A – are likely to drive their costs down (both in A and N). Fourth, changes in GDP imply changes in trading patterns between A and N. Consequently, it is difficult to assure that CL(ΔR) calculated according to either of the formulas indeed corresponds to the theoretical concept.

An OECD simulation (Burniaux et al. 2009, 2012) shows that carbon leakage should not exceed 6% when the whole Annex I is included in coalition. The carbon leakage rate is calculated as: 1-(world emission reduction)/(Annex I emission reduction objective). When the emission reduction achieved at the world level is equal to the emission reduction objective set by Annex I, there is no leakage. Winchester (2011) shows that the 20% emission reduction by Annex I countries will generate up to 25% carbon leakage. The author used a static CGE model with 2 regions (coalition and non-coalition). The smallest CL was obtained by Mattoo et al. (2009) using a recursive dynamic CGE model with 15 regions. The authors found that the leakage rate is 1%, if unilateral action of 17% cuts is taken jointly by EU and US. Also Boehringer at al. (2010) applied a static CGE model with 16 regions for the analysis climate commitments by the EU and the USA. Assuming a 20% emissions reduction, global carbon leakage rate reaches 10% in the case of the unilateral US policy and 20%-25% in the case of a unilateral EU policy, while it ranges between 10%-15% if the EU and the US undertake a joint action. The EU is exposed to a higher carbon leakage rate than the US because of its higher trade openness and more costly carbon abatement options available.

Unilateral commitments by a single region have also been analyzed by other authors. Fischer and Fox (2010) found that the leakage rate for unilateral emission reduction with auctioning permits by US is 8%. All studies confirm that unilateral commitments by US generate lower carbon leakage than by EU. Small leakage rate (11%) was found by Kuik and Hofkes (2010) with a static CGE model for 13 regions with unilateral EU policy. A CL was defined here as the increase in emissions via all channels of leakage: directly (via production process) and indirectly (via electricity consumption). Reinaud (2008) analyzed the European aluminum sector and potential carbon leakage risk for this sector. The author showed immediate loss of market share and reallocation of energy-intensive industries abroad due to uneven carbon constraints, but he argued that it is difficult to assess the exact impact of the EU emission trading system, which results from the existence of long-term electricity contracts and high demand and prices of aluminum on global markets. The primary aluminum has not suffered from carbon leakage in the late 2000s, but more ambitious climate policy goals may deteriorate its competitive position.

Loeschel et al. (2008) analyzed unilateral EU policy with a static CGE model for nine regions. Carbon leakage was estimated at the level 20% when the target for EU was 20% emission reduction. Similar results were obtained by Schinko (2010). The author found that unilateral EU climate policy implies an increase of emission in non-EU countries. The author used a static CGE model with 14 regions, where up to 22% emission reduction by Annex I countries were considered. It gave 28% of carbon leakage. The more stringent and less global climate policy is implemented, the higher the carbon leakage is. The opposite conclusion was obtained by Bossello et al. (2011). The authors found leakage rates of 74% and 70%when 20% and 30% GHG reduction targets were considered respectively for unilateral EU mitigation policy (a higher carbon leakage corresponds to a lower emission target – a result that is not typically reached). The authors used a recursive dynamic CGE model with 26 regions. Also Steininger et al. (2011) found that as climate policies become more stringent and comprehensive, the fraction of abated CO2 emissions in non-coalition regions increases. Using a recursive dynamic CGE model with 15 regions, unilateral EU policy with auctioning permits generate the leakage rate of over 50%. But even in the most stringent (40% reduction) scenario where all Annex I countries participate, carbon leakage is still above 20%.

Numerous studies suggest that the carbon leakage rate – although positive – is below 100% which means that unilateral abatement does contribute to climate protection (i.e. the increase in emissions in N due to the additional reduction in A is lower than this additional reduction in A). The global cost of abating a unit of carbon is higher than the cost which could occur under a hypothetical global agreement. This is because avoided emissions in A would need to be divided by 1-CL(ΔR). On the other hand, carbon leakage may turn out to be above 100%, if the additional emissions in N turn out higher than the additional reduction undertaken in A. In such a case, unilateral abatement is detrimental for climate protection. This can be expected when production moves to locations with higher carbon intensity (producers in N are less carbon efficient than producers in A), or positive long-run effects related to technological progress are weaker. Under some circumstances, the CL rate can be negative which means that there is no increase in emissions in N. For instance, this may happen when border tax adjustments are implemented.

It would be inappropriate *a priori* to exclude any of the cases. Historical records indicate that global GHG emissions have been growing over the last decades, despite unilateral abatement actions undertaken by some regions since the 1990s, most notably by the EU. Non-Annex I countries do not report their carbon dioxide emissions under the UNFCCC. Thus, it is difficult to assess global emissions. Nevertheless, the European Bank of Reconstruction and Development (EBRD 2011) collected some data (on 1990-2005) to conclude that the annual rate of growth in carbon dioxide emissions prior to the UNFCCC was 0.6%, then it increased to 1.2% between 1995 and 2000, but after the adoption of the Kyoto Protocol it reached 2.6%. The growing emissions in non-Annex I countries are largely related to fast economic expansion. Of course, there could have been dozens of reasons for this trend, but it indicates that – given the stabilized emissions from Annex I – non-Annex I countries' emissions are growing at an ever increasing pace which makes climate protection targets more difficult to achieve.

Beckman et al. (2009) try to explain why estimates of the cost of climate mitigation with CGE models are likely to be too low. This is mainly due to overstating the price elasticity of demand for energy and energy substitution. If elasticities are high, substituting carbon-intensive factors seems to be cheaper than it actually is. These are key parameters that are insufficiently validated within CGE framework since they are not estimated econometrically there. Using values that are in line with the literature estimates, the authors found that marginal abatement cost for GHG were underestimated by 57%. This suggests that carbon leakage is grossly underestimated consequently.

Babiker (2005) shows that CL may exceed 100% when increasing returns to scale are considered for energy-intensive sectors. Using a static CGE model with 7 regions, the author pays attention to relationship between carbon leakage and returns to scale and homogeneity of goods (both assumptions were related to energy-intensive sectors only). The homogeneity of goods means that energy-intensive products can freely compete both nationally and regionally. Carbon leakage is defined as the change in non-abating region as a fraction of the emission reduction by the abating region. When products are differentiated, the returns to scale assumption has a slight effect on carbon leakage rate. However – when perfect homogeneity is assumed – it is twice as high. The homogeneity assumption alone, irrespective of returns to scale, implies a huge jump in the leakage rate. The combination of constant returns to scale and product differentiation by origin (the usual assumption under CGE modeling) gives the lowest leakage rate – 20%. The author shows also that the leakage effect has the same direction as the welfare effect.

Hassler and Krussel (2012) found evidence for perfect leakage (no change in the climate at all) using integrated assessment model. The result that CL may exceed 100% was not confirmed by Carbone et al.

(2009) using a static CGE model with 6 regions. The leakage rate is around 50% when goods are homogenous across regions and over 20% otherwise. However, trade spillovers decrease global emissions when traded goods are imperfect substitutes. An environmental improvement will depend on whether the dominant influence of international trade is via quantities (carbon leakage) or prices (terms of trade spillovers). The carbon leakage effect will tend to diminish incentives for domestic abatement. The only source of leakage in the model comes from the response of one region, when five regions are in coalition. Marginal change in emissions can be decomposed into a direct effect (due to the change in emissions from coalition region permit choice) and an indirect (carbon leakage) effect.

Carbon leakage may also be analyzed in a broader sense taking into account the trade flows between countries. If governments take account of the impact of their policies on the terms of trade, the distortions caused by unilateral climate policy turned out to be even more complex (Eichner and Pething 2009). The one source of CL is when production and new investments shift from countries participating in carbon abatement schemes to non-participating countries, holding back the reduction of global emissions. This is because of the change in the relative energy prices in participating and non-participating countries due to the introduction of carbon pricing. Another form of leakage is when carbon pricing depresses the demand for energy in countries adopting climate policies, and with its declining price, more energy is used in nonparticipating countries. Carbon leakage could be also defined by referring directly to emissions embodied in international trade flows. Peters et al. (2011) discuss the global carbon emission flows and propose a redefinition of carbon leakage to include all emissions occurred during the production of traded products and to consider also non-climate policy induced increases in emissions. Hence, the authors propose to separate production- and consumption-based emissions and provide abundant evidence for increased emissions embodied in net exports in countries like China, India, Russia, South Africa, or Brazil in recent years.

We realize that there is evidence for 'outsourcing' pollution through the rapidly changing volume and structure of global trade. That is why there are significant differences between production-based and consumption-based emissions in many countries (OECD 2011, p. 56). However, if carbon leakage were to be attributed to the complexity of the global economic system and myriad of other factors, relating CL to changes in climate policies would be difficult to track. Peters (2008) reassures that trade is not bad for the environment, but, in our view, a decrease of carbon leakage defined in this broad sense would inevitably require some constraints on trade. This issue deserves further research, but it is beyond the scope of our paper. We apply a more standard, narrower definition of CL, where the only source of the leakage is a change in climate policy regime (a shift from the current carbon reduction target to a more ambitious target), possibly mitigated by an anti-leakage instrument.

Our definition of the CL differs from the relevant literature in three basic ways. First, a region N is usually defined as a region that undertakes no climate action. We stress that not all countries that undertake some climate action are qualified as a region A. A proper distinction between countries qualified as regions A and N is essential for the level of CL, because the results can be overestimated. Second, when several assumptions about scenarios are changed simultaneously, it is hard to find out which one causes a change in CL. We make the usual assumption ‘everything else being constant’. Therefore we try to identify single changes in given scenarios as necessary requirements to compare CL rates between alternative simulations. Third, most authors take a 'Business As Usual' (BAU) scenario with no climate action as a baseline to define CL. We assert that in baseline scenarios some climate action should be included in the case when region A already undertook some actions in the past (if we ignore it in the baseline, then CL cannot be estimated accurately).

3. Anti-leakage policy

A major challenge in the design of unilateral climate policy is the appropriate response to the threat of carbon leakage (Boehringer et al. 2011). In contrast to climate policies, anti-leakage policies have little effect on global welfare, but they might have significant effects on the EITE (energy-intensive, trade-exposed) sectors (Boehringer et al. 2010). The spectrum of anti-leakage instruments is quite broad as specific parameters of these measures may vary and offer various combinations. In order to encourage less developed countries in Annex I into climate action, Schinko (2010) shows that they should be allowed to set for themselves realistic targets instead of being subject to stringent emission targets decided by rich countries. If this option is not possible, then two perspectives can be considered.

From a regional or country perspective, anti-leakage measures ensure a (equal) level playing field for domestic tradable industries vis-à-vis their foreign competitors. First, these are measures to protect domestic producers from rising costs due to the implementation of carbon pricing. So far, an implementation of a cap-and-trade scheme in the EU (covering big emitters, usually power and energy-intensive industries) has been accompanied by allocating free allowances based on historical emissions (grandfathering scheme), and irrespective of the current or future output. An alternative measure is an output-based allocation (OBA scheme) of tradable emission permits, where the allocation of free allowances is linked to, and updated based on, the recent production levels. The output-based allocation of permits can be full or partial, as in case of the third phase of the EU 'Emissions Trading Scheme' (ETS) implementation (2013-2020) in which these allocations will be gradually phased down over time. With this instrument in place, emitters are not inclined to reduce emissions by decreasing production, while they have motivation to reduce their carbon intensity. Second, there are measures to equalize the cost of carbon, embodied in the production cycle of tradable goods, for foreign competitors. This is border tax adjustments (BTA), which usually require that importers purchase emission permits based on the carbon content of the imported goods. Alternatively, a border adjustment measure could give rebates to exported goods in order to assure competitiveness on global markets. A combination of the two measures is possible as well. The EU preserved a conditional option to introduce anti-leakage trade measures if the EU's main competitors would not engage in a comparable manner into a climate action (EC 2011).

According to Mattoo et al. (2009), BTA should be interpreted as a way to rebalance the conditions of free-trade and competition, rather than a protectionist measure. The authors analyze BTA based on the carbon content of imports versus BTA based on the carbon content in the domestic production. The former produce fewer distortions in global economy because tariffs rate are lower. Winchester (2011) compares BTA as an emission tax versus BTA as an output tax. Producer responses to tax depend on embodied emissions legislation. If embodied emissions calculations are rarely updated, firms will view BTA as a tax on exports and will not respond by reducing the GHG intensity of production. BTA defined as an emission tax can significantly reduce leakage by 20 percentage points (by 80%) when non-coalition firms operate a single production line for all markets. When firms view BTA as an emission tax and they operate a separate production line for each market, it generates a similar result as an output tax (the leakage rate is reduced by 10 pp). Steininger et al. (2011) show that BTA are only effective to halt competitiveness losses due to unilateral EU policy when the tax rate is high and EITE sectors constitute a comparatively small share of the economy.

Boehringer et al. (2011) show implications of anti-leakage instruments for unilateral 20% GHG reduction by the EU. A symmetric BTA allows reaching CL rate lower by 7 pp (by 25%) and similar result can be achieved with import tariffs only. The OBA is the least effective instrument because it works as an implicit output subsidy, but it introduces fewer distortions in the economy than BTA. If the US follow the EU commitments, then the leakage rate decreases by 10 pp and BTA will reduce it by additional 5 pp. Future coalitions will have a proportional effect. With grandfathering permits, according to Bossello et al. (2011) the leakage rate decreases by 14 pp (by 20%) because the initial economic signal towards low carbon intensity disappears. BTA on imports is able to reduce carbon leakage by 9 pp, but not 'economic leakage' because the competitiveness of non energy-intensive sectors (using energy-intensive inputs anyway) is affected. The EU carbon price almost doubles when moving from unilateral to multilateral commitments due to a lower reduction of demand for EU goods.

Different results were obtained by Kuik and Hofkes (2010). They show that BTA have modest effect on carbon leakage but sectoral effects are considerable for steel industry. This may be explained by the scenario definition: the authors consider BTA on imports for selected sectors only (steel and mineral). However the authors give an alternative explanation for this difference: the energy channel is important for macro level, but not for sectoral level. The leakage rate can be reduced only by 1 pp when the import tariff is based on direct emission per unit of similar product in EU or by 3 pp when the import tariff is based on direct emission per unit of production of a similar product in non-EU. The authors conclude that BTA effectively reduces the leakage rate through the trade channel, but does not affect the energy channel.

McLure (2010) regards economic, administrative, and legal issues related to border adjustments for carbon taxes and the costs of emissions permits. Origin-based BTAs are violations of the provisions of GATT, but 'it seems quite possible' that import BTAs would be granted an exceptional treatment, while it is unlikely for export BTAs[3]. The author emphasizes that calculating the appropriate BTAs, based on the carbon content of imports, would be extremely complicated. Hence, it is likely to be applied to a relatively small number of energy-intensive products, compensating just for direct and indirect carbon prices incurred in their production.

Fischer and Fox (2010) found that the choice of auctioning or grandfathering has little effect on CL. The authors adopted a static CGE model to investigate the effect of unilateral emission reduction by the US. OBA targeted to EITE sectors can bring higher welfare and lower emissions leakage. Granting OBAs to less trade-intensive sectors (like electricity) can further lower the leakage, but at a significant welfare cost if the remaining allowance revenues would otherwise substitute for lower distorting taxes in the economy. Another approach was used by Llavador et al. (2010), where a model covers only the US and China in order to find out the allocation of emissions that will allow converging (in welfare per capita) both economies. The baseline assumes that China and the US would converge in GDP per capita in 75 years, but emissions control implies that the two countries' GDP would converge in 100 years. The transition paths require a drastic reduction of the share of emissions allocated to US, large investments in knowledge both in US and China, very large investments in education in China, and some output must be transferred from China to US during the transition. As far as consumption loss is considered in the abated regions, according to Boehringer et al. (2010), BTA via export rebates are more costly for those regions than OBA, BTA via import tariffs, and full border adjustment (both export rebate and import tariffs), respectively. However, any specific anti-leakage measures cannot reduce the leakage by more than 33%. The rest of leakage is due to lower global energy prices and increased global demand for fuels

[3] According to the German Federal Environmental Agency (Umweltbundesamt 2009), environmentally motivated border tax adjustments are admissible under WTO obligations.

in other regions. The authors emphasize that the largest global economic effects stem from carbon pricing itself rather than from unilateral commitments and anti-leakage trade-related measures.

From a global perspective, the available measures are aimed at preventing carbon leakage, with the global climate agreement being an optimal solution, or reducing it through an effective mechanism of alternative carbon offsets. As reaching a global agreement seems to be a distant perspective, we focus on the latter as a more feasible solution. Even in a world where countries only pursue their national self-interest, an international system of tradable emission permits can achieve substantial emission reductions (Carbone et al. 2009). Currently available mechanism CDM is regarded as an outreach to non-Annex I countries. However, the fact that host countries do not take any binding commitments raises questions to what extent such policies contribute to global CO2 emission abatement. Effective carbon offsets could lower the carbon price in Annex I countries, as the GHG reduction efforts would be undertaken in places where it is most cost-effective, and thus mitigate the risk of carbon leakage. However, given no binding commitments in non-Annex I countries and unclear baseline emissions paths, ill-structured offsetting mechanism may lead to higher carbon dioxide emission in developing countries. We confirm this possibility in our simulation analysis with a CGE model.

The OECD simulation (Burniaux et al. 2009) shows that CDM lowers the carbon price differential with nonparticipating countries. However, whether crediting mechanisms reduce leakage depends in part on appropriate setting of the baseline against which credits are granted. If the baselines are too high (the case when emission level in non-Annex I countries corresponds to the level after Annex I takes action, i.e. already incorporates some leakage) crediting mechanisms basically reallocate emission cuts across regions, without addressing the leakage to non-coalition regions that occurred in the first place. Of course, an allocation of binding emission reduction commitments across countries would be the most cost-effective. Habla and Winkler (2011) show that global emissions may be higher in an international cap-and-trade system compared with unilateral policies. It is a consequence of 'hot-air' where low damage countries issue more permits than they actually emit in order to sell excess permits on the international market. The non-cooperative game of an international emissions permit market shows that there is no single solution and total emission depends on economic and political parameters related to lobby groups. Using a recursive dynamic CGE model with 12 regions, Klepper and Peterson (2005) show that welfare gains in hot-air economies are smaller than the negative welfare externalities in the other regions. The amount of hot-air supplied will be small if hot-air economies cooperate in their decisions.

Loeschel et al. (2008) show that integrated emission trading induces a considerably lower leakage rate than the BTA scheme, but the global emission will decrease by around 2% in any scheme. DeCian and Tavoni (2010) analyze the macroeconomic and financial consequences of delayed establishment of an international carbon market instead of planned 2020. When moving from the full offsets hypothesis to the limiting case of no international offsets until 2045, the costs of the climate policy increase by 50%. Policy costs in Europe are shown to be more sensitive to ceilings than those in the US, especially for the more stringent cases.

Previous studies accepted that something changes in regions with non-abating policy (including Annex I countries that do not take up targets), whereas we assume that there are no policy changes in those regions. We would like to answer the question whether unilateral emission reduction in region A (that is the EU only) can significantly reduce global emissions. Our simulation experiment covers four anti-leakage measures: BTA via import tariffs, OBA, CDM, and CDM with ill-structured offsetting mechanism.

We followed the approach of other researchers and applied a multi-region and multi-sector CGE model in order to simulate the impact of climate policy and anti-leakage measures on the entire economic system.

4. Global CGE model and scenarios

CGE models are robust tools to assess the economic effects of the anti-leakage measures. We have preceded the description of our model and policy simulations with a review of relevant models in previous sections.

Our simulation experiment is based on the global CGE model developed by C. Boehringer and T.Rutherford, commissioned for a World Bank report (2011a). The *Regional Options of Carbon Abatement* (ROCA) model is a static multi-sector, multi-region CGE model, based on the GTAP7 database (Narayanan and Walmsley 2008) with 2004 as the base year. The model was primarily used to analyze the economic effects in Poland associated with the implementation of the EU 20-20-20 policy in the context of global policy scenarios. The model incorporates market distortions (like the existence of initial taxes) and market imperfections (like labor market rigidities) that may change the costs of carbon abatement. Power sector production is represented in a hybrid bottom-up/top-down manner in the original model, but this decomposition was redundant for the purpose of our paper, and it was simplified to classical top-down manner.

Production technologies in all sectors are described in a conventional way with a nested CES function using capital, labor, and energy as production factors – see the Appendix for the illustration. Global coverage of international trade and energy use across 3 regions (EU, other industrialized economies - A1, and developing countries - DC), grouped out of 113 countries from the GTAP7, enables analysis of international spillovers and feedback from climate policies on global energy prices. The original 57 GTAP sectors were grouped into 13 sectors: 5 EITE sectors (chemicals, non-metallic minerals, iron-steel, non-ferrous metals, paper-pulp-print), 5 energy sectors (coal, natural gas and heating, crude oil, refined oil-coke-nuclear fuels, electricity), 2 transportation sectors (aviation and other transport), and other manufactures and services including renewables. Only two of those sectors are not covered by the EU ETS: other transport and other manufactures. The Table 1 includes the details of the model sectors and regions. We distinguish between combustion of coal, gas, and oil. The "coal" is defined in the model as hard coal, lignite and peat, but it does not include coke. The coke is included into "oil" together with petroleum products and nuclear fuels. A crude oil is defined separately and it is not a direct source of carbon emission. The "gas" is defined as natural gas, gaseous fuels, steam and hot water according to the GTAP definition. The database does not allow for separating heating from gas. This means that we should be careful with result interpretation for the gas sector.

Table 1. Composite database of the model ROCA+

Grouping of 57 sectors and commodities		***Grouping of 113 countries and regions***
Energy sectors	*Sectors covered by the EU emission trading system*	*Regions with Kyoto emission reduction pledges*
Coal (COL)	ETS/non-EITE	1) EU27 (EU)
Crude oil (CRU)	ETS/non-EITE	2) remaining countries in the

Natural gas & heating (GAS)	ETS/non-EITE	Annex I (A1)
Refined oil products, coke, nuclear fuels (OIL)	ETS/non-EITE *	
Electricity (ELE)	ETS/non-EITE	
Non-energy sectors		*Regions without emission pledges*
Chemical industry (CRP)	ETS/EITE	3) non-Annex I countries (DC)
Air transport (ATP)	ETS/non-EITE	
Other transport (TRN)	non-ETS	
Non-metallic minerals (NMM)	ETS/EITE	
Iron and steel industry (I_S)	ETS/EITE	
Non-ferrous metals (NFM)	ETS/EITE	
Paper–pulp–print (PPP)	ETS/EITE	
Other manufactures and services including renewables (OTH)	non-ETS	

ETS – Emission Trading System; EITE – energy intensive and trade exposed sectors
* OIL is not included into EITE sectors in the model in order to treat all fuels similarly

The model's horizon stretches to 2020, which is the deadline for the EU 20-20-20 package obligations. Trade is specified following the Armington approach, i.e. assuming product heterogeneity of domestic and foreign goods, which turns out to be a critical assumption for the risk of carbon leakage. Domestic production either enters the formation of the Armington good or is exported to satisfy the import demand of other regions. Countries are represented only by regions, i.e. no substitution is possible between countries within a region. Carbon emissions are linked in fixed proportions to the use of fossil fuels, which have different carbon content. Carbon reduction takes place either by fuel switch (a limited substitution between coal, gas, and oil) or energy savings (reduction in economic activity). Non-CO2 emissions of greenhouse gases are not considered in the model. The only source of carbon emission in the model is combustion of fossil fuels.

There are 3 primal production factors (labor, capital and resource) and 4 energy factors (oil, gas, coal, and electricity). Labor and capital are mobile across sectors but not between regions, while resource is sector and region specific. Unemployment is determined by wage curve. Capital stock is determined by investment level – and likewise investment, fixed on the level calibrated to 2020. Sectoral resource supply is calibrated to match exogenously given level of fossil fuels use and their prices. Final demand in every region is modeled in a similar manner to production function (Figures 6-8). On the bottom level we have substitution between fossil fuels, then between fossil fuels composite and electricity and finally between energy composite and composite of other goods. Households furthermore substitute between consumption and leisure activity. It should be noted that because final demand functions are nested-CES type, we cannot capture income effects in our model. We don`t have consumption-saving decision. Instead, investments are fixed to the level calibrated to 2020.

We revised and updated the original ROCA model, and together with the new name "ROCA+" we introduced the following modifications. Data for all EU countries were integrated into a single region (EU), while the sector grouping was kept unchanged. The business as usual scenario (BAU) was updated. Changes in the BAU scenario for the EU led to different effective carbon abatement targets and hence they are different from nominal targets defined against the 2005 levels. For example, the nominal GHG reduction target for the EU of 14% relative to 2005 corresponds to an effective target of 15.5% relative to BAU 2020. We made revisions in the mitigation targets across regions and assumptions across sectors in the ROCA+ model, and their details are discussed below.

In a World Bank study (2011a), the ROCA model was applied to run various policy scenarios. They were related to: carbon market segmentation, restrictions on use of carbon offsets, overlapping climate regulation, recycling options of revenues from carbon pricing, technological constraints in the power sector, output-based allocations of free emission allowances to EITE sectors, regarded as vulnerable to carbon leakage. Our analysis is confined to the carbon leakage scenarios, assuming more ambitious mitigation targets by the EU, and alternative scenarios for the rest of Annex I and developing countries. We investigate how the carbon leakage rate changes when:

a) the EU adopts more ambitious targets without a comparable effort in other regions (REF and HIGH scenarios),
b) compensating measures are introduced to protect domestic producers (OBA and BTA scenarios),
c) developing countries participate in the climate action through international offsets (CDM and CDMnew scenarios).

All policy scenarios are compared with BAU scenario that assumes economic and environmental forecast for 2020 in line with the base case by the International Energy Outlook (Energy Information Administration 2009). No emission limits are applied. In the baseline scenario world energy-related carbon dioxide emissions grow from 26 Gt in 2004 to 36 Gt in 2020. Anthropogenic emissions of carbon dioxide result primarily from the combustion of fossil fuels, and it is the only source of CO2 emission in the model. World consumption of oil grows by 25% from 2004 to 2020, while coal and gas by 40% and 60% respectively. Future world oil prices significantly increase to 2.85 relative to the 2004 unit price index. World price of gas and coal is 1.4 and 1.1 respectively. GDP in EU and other Annex I countries will grow by 40%, but in DC by 130%. Total energy-related carbon dioxide emissions grow by 40% as a result of increase by 4% in the EU, by 13% in the rest of Annex I, and by 70% in DC.

The reference (REF) scenario assumes an emission reduction target of 15.5% for the EU (a 21% reduction in the ETS and a 10% reduction in non-ETS sectors (according to EC (2010b, p.32)), and a 4% reduction target for the rest of Annex I (according to UNFCC data), all relative to 2004 (base year in our database). As suggested by its name – the scenario includes a central set of assumptions, with respect to which alternative scenarios are benchmarked using a set of headline outcome indicators (welfare, output, carbon prices, etc). The target for EU is consistent with the 2009 Copenhagen Accord under UNFCC of 20% reduction versus 1990, but Annex I countries other than the EU will support only reduction targets of the 1997 Kyoto Protocol. We want to show consequences of a unilateral switch by the EU from Kyoto to Copenhagen obligations. The official EU documents (European Commission 2010a) set emission pledges for ETS and non-ETS sectors relative to 1990 or 2005, but the model covers database for 2004. However, the EU emission changed only slightly from 2004 to 2005: it was 3981 Mt CO2 in 2004 and 3956 Mt CO2 in 2005. Thus we have assumed pledges relative to 2004 the same as for 2005.

Cost-efficient environmental regulation implies that endogenous carbon tax is applied for all sources of emission, but we provide an exemption for final consumption. It is an alternative solution to a region-wide emission trading with an auctioning scheme for energy-intensive industries. Each EU country imposes a domestic tax for non-ETS sectors, while the remaining Annex I countries set a uniform carbon tax for all sectors. The revenue from emission permits or carbon taxes are recycled back into economies as a lump-sum to households, keeping equal yield constraint for governments. The main characteristics of the Reference and alternative policy scenarios are summarized in Table 2.

In order to compare our scenarios with the original version of the ROCA model, we have replicated the original reference scenario from the ROCA model with the ROCA+ model (MAIN_ROCA scenario). It assumes a relatively high elasticity of substitution (2.0) for the power sector between fossil fuel inputs. We have changed it in the other ROCA+ scenarios to 0.9 in order to show that it is relatively more difficult to substitute fuels. Elasticity of substitution between capital and labor is zero in some energy sectors (COL, GAS, CRU) in the ROCA model, but we changed it in the other ROCA+ scenarios to 0.5 in order to show that some substitution is possible. The wage curve elasticity is assumed 0.8 for ROCA, and we have reduced it to 0.5 for ROCA+. In sensitivity tests, we found that none of those modifications, except for the elasticity of substitution in the power sector, had an influence on carbon leakage.

Assumptions of emission limits for non-EU Annex I countries and the application of CDM do matter. When only EU countries have reduction pledges, carbon price decreases. When CDM is restricted, then carbon price goes up. The original MAIN_ROCA scenario assumed pledges for Annex I to be 4.8% relative to 2004. It allowed for the application of CDM only for EU, but with a limit of 20% and 33% of the reduction target for the ETS and non-ETS sectors, respectively. We changed it in the REF scenario of the ROCA+ model to 4% pledges for Annex I, but at the same time we allowed for no clean development mechanism. This is because we want to show separately how alternative instruments may influence the carbon leakage. Overall, the MAIN_ROCA and REF assume the same emission pledges for the EU, but combined with different pledges for A1 countries, and different assumptions about CDM. As a result, the total emission reduction is 7% in the MAIN_ROCA and 6% in the REF.

In the LOW scenario, pledges for the EU are lower than in REF scenario, while other assumptions remain unchanged. It considers a hypothetical EU policy of 8% CO2 reduction relative to 1990 in line with the Kyoto Protocol commitments. A similar scenario was simulated by the PRIMES model[4] (EC 2010b) with different pledges for ETS and non-ETS. Taking these assumptions, we set emission limits at 90% for the ETS and 98% for the non ETS of the 2004 levels. This gives the total emission reduction of 6% in EU relative to 2004. However, PRIMES simulates carbon price in ETS €25 (expressed in the 2008 prices), but our model calculates endogenous price equal to $21 (expressed in 2004 prices). In order to replicate PRIMES projections more accurately, we could substitute International Energy Outlook forecast in our BAU scenario with the PRIMES results at a non-zero carbon price. This could be a future extension of our model. By now, we tested that taking into account the PRIMES forecast of economic growth in EU within our model and setting zero carbon price and no emission limits, the ROCA+ model generates 2020 emissions in the EU 7% below their 2004 level. This validates the results generated by the ROCA+ model, because endogenous emission reduction level is in line with Kyoto obligations.

Table 2. Policy scenarios

Characteristics / Scenario	BAU	REF	LOW	HIGH	BTA	CDM	CDM_NEW	OBA	MAIN_ROCA
Carbon reduction targets, in % relative to 2004									
EU	0	16	6	25	16	16	16	16	16
EU ETS	0	21	10	34	21	21	21	21	21
EU non-ETS	0	10	2	16	10	10	10	10	10
Rest of Annex I (A1)	0	4	4	4	4	4	4	4	4.8

[4] It is a partial equilibrium model for the European Union energy markets that is widely used by the European Commission to analyze climate strategies.

Developing Countries (DC)	0	0	0	0	0	0	0	0	0
Allocation of emission allowances and carbon tax by sectors									
OBA	-	-	-	-	-	-	-	EU ETS/ EITE	-
Auctioning (with lump-sum recycling)	-	EU ETS	EU ETS	EU ETS	EU ETS	EU ETS	EU ETS	EU ETS/ non-EITE	EU ETS
Carbon tax (with lump-sum recycling)	-	EU non-ETS A1	EU non-ETS A1	EU non-ETS A1	EU non-ETS A1	EU non-ETS A1	EU non-ETS A1	EU non-ETS A1	EU non-ETS A1
Border carbon adjustments based on carbon content of traded goods									
Import tariffs	-	-	-	-	EU A1	-	-	-	-
Use of international carbon offsets									
baseline emission level in DC	-	-	-	-	-	before CO2 trading	after CO2 trading	-	before CO2 trading
Export premium for DC	-	-	-	-	-	yes	yes	-	no
Limit as a % of reduction target in EU ETS	-	-	-	-	-	20%	20%	-	20%
Limit as a % of reduction target in EU non- ETS	-	-	-	-	-	33%	33%	-	33%
Limit as a % of reduction target in A1	-	-	-	-	-	100%	100%	-	0%

Note: A sign "-" means that the given option is not applicable.

Similarly, in HIGH scenario pledges for the EU are higher (more ambitious) than in REF. It considers a possible future EU policy of 30% CO2 reduction relative to 1990 in order to support high pledges of the Copenhagen Accord. The European Commission (2010a) sets high pledges for ETS and non-ETS versus 2005 as 34% and 16%, respectively. We assigned the same limits in the model, and it corresponds to the EU total emission reduction of 25% relatively to 2004.

Border tax adjustment scenario (BTA) considers one of the contemplated instruments to reduce carbon leakage in the absence of a global climate agreement. Border taxes on imports are imposed by EU and the rest of Annex I on all imported products. The tax rate is based on the carbon content of imported goods:

$$BT_{I,S,A} = PC_{I,N} - P_{I,N} = P\_CO2_A * c_{I,N} \quad (3)$$

where BT is a tariff rate applied by region A on imported product i from region N, $PC_{I,N}$ and $P_{I,N}$ are respectively a consumer and producer prices of imported product i from region N, P_CO2_A is a domestic price of carbon in region A, $c_{I,N}$ is an emission intensity parameter for the imported product i from region N. Future research could cover alternative definitions of tariff rates based on the carbon content in domestic production and a full BTA, which comprises both import and export adjustment. Also, alternative instruments like taxation of international transport could be evaluated.

A combination of free emission permits in selected sectors and full auctioning in the remaining sectors is assumed in output based allocation scenario (OBA scenario). Compared with the assumptions for REF scenario, in OBA scenario emission permits are grandfathered for EITE industries (chemical, minerals, metals, and paper). Among the EITE, chemicals, nonferrous metals, iron, and steel are exposed to carbon leakage risk most (Boehringer et al. 2010). These sectors account for a relatively small share in overall emissions and production activity in the EU, but unilateral emission limits raise concerns about their competitiveness. Thus a free allocation of emission allowances to EITE industries may help to keep their competitiveness *vis-à-vis* economies that lack comparable environmental regulations. The allocation of free permits in the model is updated based on sectoral outputs, and it covers 100% of the emissions in the eligible sector. It is handled as an implicit production subsidy contingent upon firms' production decisions:

$$OS_I = P\_CO2 * b_I / Q_I \tag{4}$$

where OS_I is a subsidy rate for sector I in the EU, Q_I is a domestic output of product I, P_CO2 is a carbon price for ETS sectors, b_I is an emission parameter based on sectoral carbon emissions in 2004 increased by emission pledges for 2020. It means that revenues of sectors getting free allowances are increased by ($P\_CO2 * b_I$). Additional allowances are granted if production increases, and carbon price constitutes an incentive to reduce emission intensity. The welfare loss linked to production subsides will be very small compared to the REF scenario because EITE sectors account for a small share only in total EU emissions and output (around 10%).

Finally, we apply two scenarios with clean development mechanism (CDM and CDM_NEW scenarios). In both scenarios, it is not important whether this mechanism is formally attributed to region A or N: abating region has binding emission limits, non-abating region has not, and clean development mechanism influences on carbon leakage in addition to lower the abatement cost. A scenario CDM coincides with the REF scenario, but some inter-regional emission trading is allowed. Broadly in line with the EU rules, a fraction of emission reduction obligations in the EU can be achieved outside the EU: ETS and non-ETS sectors are assumed to purchase up to 20% and 33% of their emission reduction requirements, respectively, according to the EC (2008 and 2009)[5]. This means that only a part of EU member states' emission reductions can be covered through an additional abatement in DC region, but no limits for international trading with DC are applied for other Annex I countries. By contrast, the original ROCA model assumed that only EU participates in inter-regional trading with DC. Equalization of reduction costs in EU and A1 regions with a cost of acquiring offset units, means that difference between reduction cost in DC region and EU or A1 region is included in export and import premiums. This can be seen in the following equation:

$$P\_CO2_A = P\_CO2_N + PX_N + PM_A \tag{5}$$

where P_CO2 is a carbon price in region A (EU or A1) with emission targets, P_CO2_N is the marginal abatement cost in region N, having no emission obligations, PX_N is an export premium for a government in region N, while PM_A is a an import premium for a government in region A. It means that the total

[5] The annual use of credits by each EU member (non-ETS sectors) shall not exceed 3% of the greenhouse gas emissions in 2005 according to EC(2009). We implemented 3.3% (it correspond to 33% of the 10% reduction) with respect to 2004. The limit for ETS sectors corresponds to the highest limit for a single EU member according to the EC (2008).

premium is divided between exporting and importing regions. If there is no export limit for emission reduction in region N (i.e. supply in DC is greater than demand in EU and A1), then PX_N=0 and the whole premium is taken over by a government in region A. If the export limit for emission reduction is not greater than demand on emission reduction by region A, then PX_N>0 and PM_A goes down. The original ROCA model considers the first option, while the ROCA+ model adopts the second option. No limit of international carbon offsets for A1 drives import premium for A1 to zero.

The CDM_NEW scenario applies a different assumption regarding CO2 emissions in DC region. If the initial emission level (before inter-regional emission trading) in DC is at the BAU level, then – by definition – no leakage is possible. In this situation, DC region indeed participates in the global climate action, and this assumption was applied in the previous CDM scenario. However, because the DC region has no binding carbon reduction target relative to BAU level, it has an incentive to inflate its emission level before trading with the EU or A1 regions. In such a case, after the completion of the carbon offset transaction, emissions in DC reach the BAU level. Although this scenario helps decrease the marginal abatement cost in the EU or A1 region, it leads to a significant carbon leakage.

5. Simulation results

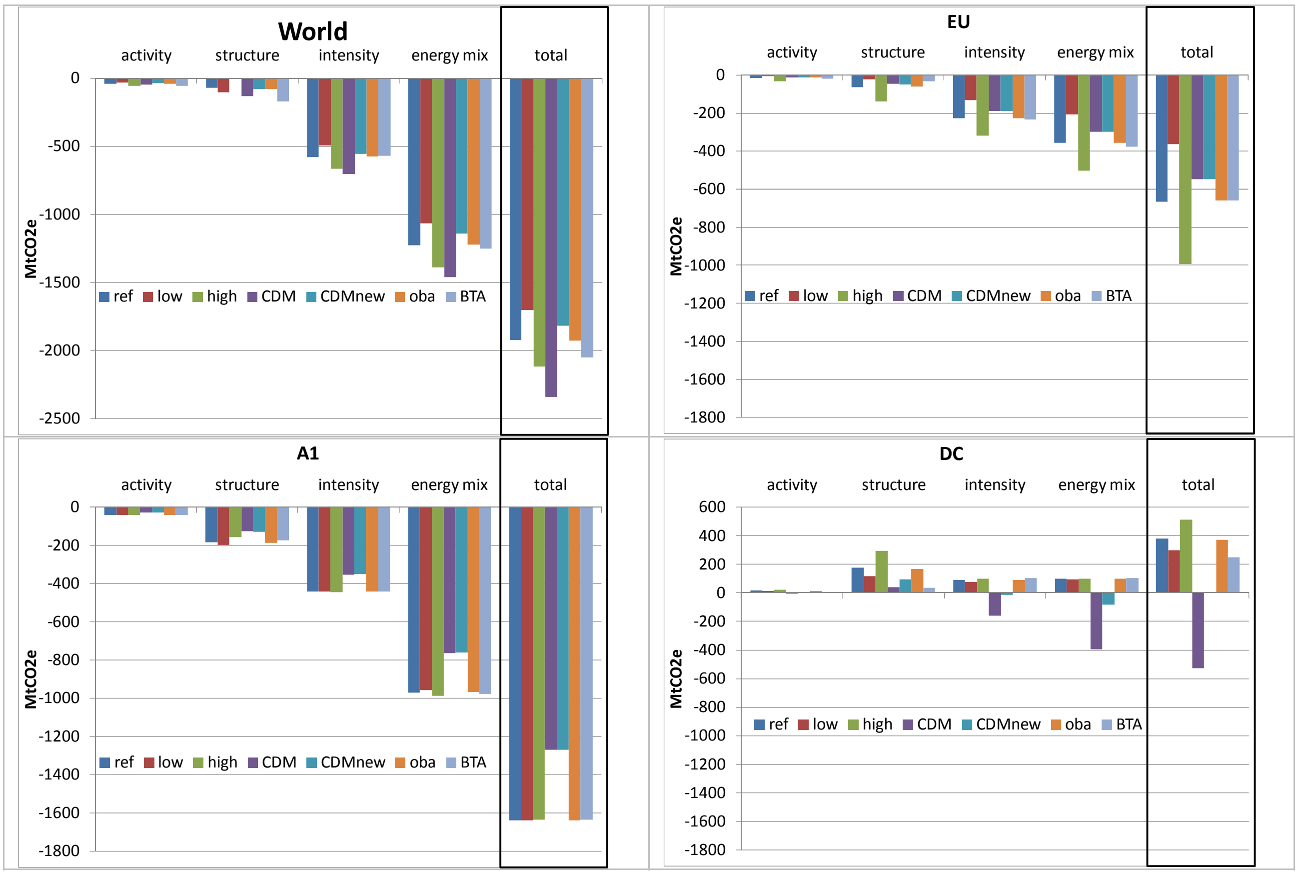
We start our presentation of the results of the policy simulations with an illustration of emission developments in the seven scenarios. What drives global and regional emission relative to their BAU levels? Global emissions decline least in the scenario with the least ambitious level – LOW (Figure 1). The biggest reduction in carbon emissions is achieved if all regions indeed participate in the climate action (CDM scenario), while the reductions delivered by the remaining scenarios are lower. Relative to BAU levels, the reduction of global emissions is between 5% (LOW) and 7% (CDM) – see also Table 5 further in this section. In all scenarios, the EU demonstrates the highest carbon reduction efforts as a percentage of the BAU emissions, but the reduction is the largest in the A1 countries because of their size. DC countries increase their emissions in all scenarios, except CDM and CDMnew. In the latter, emissions in DC remain at their BAU level. In the remaining cases, the emissions in DC go up, while this growth is somewhat contained if the rest of the world introduces an import tax based on the carbon content (BTA scenario).

Changes in carbon emission from sectors may be studied by quantifying the impact by several factors. We use additive decomposition with LMDI (Divista Index in the Logarithmic Mean) method specification (Ang 2005), where four factors are considered:

1) Activity effect shows overall regional activity ($\sum_I Q_{I,R}$) in a given scenario relative to BAU;
2) Structure effect shows activity mix ($Q_{I,R}/\sum_I Q_{I,R}$) in a given scenario relative to BAU;
3) Intensity effect shows sectoral energy intensity ($C_{F,I,R}/Q_{I,R}$) in a given scenario relative to BAU;
4) Energy mix effect shows fuel mix ($C_{F,I,R}/\sum_F C_{F,I,R}$) in a given scenario relative to BAU;

where $Q_{I,R}$ is an output in sector I in region R, and $C_{F,I,R}$ is the consumption of fuel F (coal, oil, gas) by sector I in region R.

Figure 1. Decomposition of the change in carbon emissions, by region (relative to BAU)



What are the main messages from the emission decomposition? The *first* result is reassuring for policy makers - the activity effect is insignificant in all policy scenarios. This is consistent with the macroeconomic results (Table 3), and showing that welfare/GDP deviation from BAU is less than 1 percent. Only in the HIGH scenario, the decline in EU's GDP is 1.7 percent, but this still can be regarded as fairly small. *Second*, the largest emission reduction in the EU and A1 results from a change in energy mix (a switch towards less carbon intensive fuels) – this effect is responsible for about two thirds of the total reduction. This is possible through a dramatic phase-out of coal, and partly gas, and a minor reduction in oil production, but combined with higher imports of electricity. This leads to increased emissions in DC, which is the essence of the carbon leakage phenomenon. *Third*, the intensity effect is responsible for about one quarter of emission reductions in the EU and A1 countries thanks to a shift towards less energy-intensive production technologies. Energy efficiency increases. Finally, changes in economic structures contribute about 10% to a decline in emissions in the EU and A1 countries. These economies have already accomplished a major shift towards services, which are less carbon intensive than industry, and this effect could not be large in the future. The structure effect is more important in DC, though it leads to higher emissions there. Thanks to this effect, in BTA scenario the DC's emissions are being contained as compared with other scenarios. Although the magnitude is relatively small, this result may suggest that import taxes based on carbon content would provoke a structural reallocation of resources in the DC economies towards less carbon intensive sectors.

Table 3. Macroeconomic results by scenario

Scenarios	Welfare [% deviation from BAU]			GDP [% deviation from BAU]			Unemployment rate [pp deviation from BAU]		
	EU	**A1**	**DC**	**EU**	**A1**	**DC**	**EU**	**A1**	**DC**

LOW	-0.1	-0.3	-0.1	-0.2	-0.5		-0.05	0.1	0.2	0.01
REF	-0.5	-0.4	-0.2	-0.7	-0.5		-0.1	0.3	0.2	0.02
HIGH	-1.2	-0.4	-0.3	-1.7	-0.5		-0.2	0.6	0.2	0.04
	Trade balance [% deviation from BAU]			**Carbon price [USD 2004 per t CO2]**				**Electricity price [% deviation from BAU]**		
	EU	**A1**	**DC**	**EU ETS**	**EU non-ETS**	**A1**	**DC**	**EU**	**A1**	**DC**
LOW	-0.1	-1	2	21	21	30	-	5	13	-0.6
REF	-7	-0.4	2	49	96	31	-	11	13	-0.8
HIGH	-18	0	3	118	197	32	-	24	13	-0.9

Note: The welfare indicator is the Hicksian equivalent variation and it relates only to current consumption (environmental benefits are not taken into account).

Table 3 summarizes the most important outcomes for three scenarios: REF, HIGH, and LOW. Welfare negatively reacts to the emission ambition level as no benefits from emissions reduction were considered in the model. It is worth noting that these adverse effects affect the developing countries as well. Their welfare decreases as a result of repercussions observed in their importing partners, i.e. the European Union and the rest of Annex I countries. In Annex I regions, both welfare and output losses, and increases in unemployment rates are manageable, only in HIGH scenario the loss in EU's GDP is more than 1 percent (1.7%). However, the EU loses its competitiveness, and the trade balance goes down considerably. A1 countries will improve their trade balance with higher emission target in the EU, since they keep their emission target constant.

Higher carbon reductions are reflected in higher carbon prices, which drive the double-digit increases in relative prices of electricity in the EU and A1 regions. Electricity price growth in the A1 is higher than in the EU for scenarios LOW and REF. In the LOW scenario, it results from carbon price and carbon intensity higher in A1 than in the EU. The share of net fuel cost in the total cost of electricity production is 19% in EU and 31% in A1 for scenario BAU. When low carbon limits are implemented, this share is decreased by 2pp in both regions, because carbon cost (its share is 6% and 13% respectively in the total cost of electricity production) drives the gross fuel cost up. In the REF scenario, the slightly faster growth of electricity price is driven only by carbon intensity of power generation in the A1 higher than in the EU. This is associated with a relatively lower penetration of low-carbon power supply. Thus industries in the rest of Annex I countries have to buy more permits to emit than industries in EU paying lower price, but the growth of electricity cost is higher. With higher emission target (HIGH scenario), the electricity price grows faster in the EU than in A1, because the share of carbon cost becomes greater than the cost of fuel purchase. Lower demand on energy in A1 and EU generate a lower price on fuels, and the production of electricity in DC becomes cheaper since they do not have any emission targets.

The carbon price in A1 slightly increases (regardless of constant emission target in all three scenarios) as a result of weaker economy in the EU. It is higher in A1 than in EU in the LOW scenario since there are higher emission targets for A1 than for EU relative to BAU. The reduction target relative to 2004 (4% and 6% in A1 and EU respectively- see Table 2) corresponds to 15% and 9% emission reduction relative to BAU as a result of higher energy consumption in A1 according to the forecast by IEA. The shadow carbon price in the non-ETS sectors is similar to the EU wide ETS in the LOW scenario, but significantly differs in other scenarios. This result suggests that the marginal abatement cost is similar for ETS and non-ETS sectors with the respective emission targets applied in the LOW scenario. This means that the European Commission allocated the Kyoto targets between ETS and non-ETS cost-effectively. However, targets distribution proposed by the EC in the second commitment period (scenario REF) is far from being efficient, since the marginal abatement cost is significantly higher in non-ETS.

Our next exercise was to address instruments considered remedies for 'free riding' behavior implied by unilateral carbon abatement actions. These are Output Based Allocation (OBA scenario), Border Tax Adjustments (BTA scenario) and two versions of Clean Development Mechanism: 'traditional' (CDM scenario), and the one where DC countries maintain their emissions at their BAU level (CDMnew scenario). Table 4 shows that these instruments are likely to mitigate welfare and output losses in the EU and A1 countries. Welfare losses do not include potential gains from a better environment in our analysis. OBA and BTA protect EU markets from imports and this helps to slow down decrease of welfare and output. Also Clean Development Mechanism allows for improvement, because targeted emissions are reached cheaper, and it helps to reduce the carbon price and lessen slightly the pressure on increased relative prices of electricity. The welfare effect for developing countries is most detrimental under the Border Tax Adjustment regime, and modest under both variants of the Clean Development Mechanism. Apparently, positive welfare changes in Annex I countries let the DC region enjoy better results thanks to international trade effects.

Table 4. Macroeconomic results for anti-leakage measures

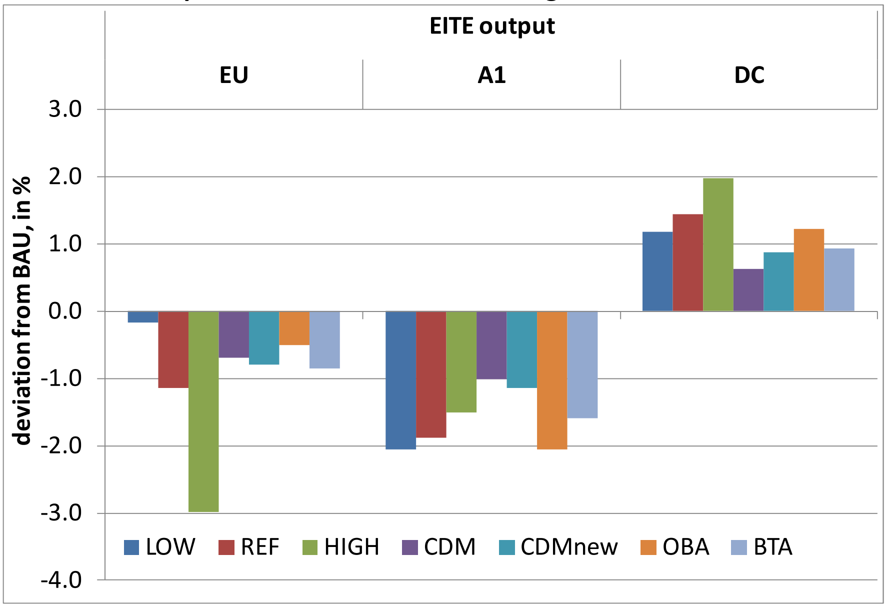
Scenarios	Welfare [% deviation from BAU]			GDP [% deviation from BAU]			Unemployment rate [pp deviation from BAU]		
	EU	A1	DC	EU	A1	DC	EU	A1	DC
REF	-0.5	-0.4	-0.2	-0.7	-0.5	-0.1	0.3	0.2	0.02
CDM	-0.3	-0.3	-0.1	-0.5	-0.4	-0.1	0.2	0.1	0.05
CDMnew	-0.3	-0.3	-0.04	-0.5	-0.4	-0.03	0.2	0.1	0.03
OBA	-0.4	-0.4	-0.2	-0.7	-0.5	-0.1	0.3	0.2	0.02
BTA	-0.3	-0.4	-0.5	-0.7	-0.5	-0.2	0.3	0.2	0.02

Scenarios	Trade balance [% deviation from BAU]			Carbon price [USD 2004 per t CO2]				Electricity price [% deviation from BAU]		
	EU	A1	DC	EU ETS	EU non-ETS	A1	DC	EU	A1	DC
REF	-7	-0.4	2	49	96	31	-	11	13	-0.8
CDM	0	1	-2	36	58	20	2	8	9	1.3
CDMnew	-0.2	1	-2	36	58	20	1	8	9	0.0
OBA	-7	-0.4	2	50	89	31	-	11	13	-0.8
BTA	-37	-2	2	53	104	31	-	12	13	-1.0

The anti-leakage measures may preserve output in sectors which are vulnerable to carbon leakage but cannot provide a solution to a global climate problem. From the EU perspective, the OBA scenario seems to be the most effective one (Figure 2). From the A1 perspective, the OBA is the least favorable because an output from EITE sectors in EU is not reallocated to A1 and DC. In all scenarios, except HIGH, output losses in EU EITE are smaller than in REF. On the other hand, unilateral actions of the EU may change the global emissions only marginally. Under the most ambitious EU scenario (HIGH), the global emissions are 7% below BAU level, which is only 1 percentage point below REF and 2 percentage points below LOW levels (Table 5). Under other A1 countries perspective, higher emission target in EU helps EITE sectors in A1 (scenario LOW versus REF and HIGH).

Global emission will be reduced in all scenarios, especially in HIGH and CDM (Table 5). Scenarios REF, OBA and BTA give the same effect on global emission, but the leakage rate is different. According to the definition provided in the Section 2, carbon leakage rate for the policy to move from LOW to REF amounts to 22%, which is moderate. The rate can be slightly reduced to 19% if some domestic producers in EITE sectors are protected through free emission allowances (OBA scenario). Carbon taxes on imported goods (BTA scenario) seem to be a much more effective anti-leakage measure, because CL rate turns negative with emissions decline in DC. The effect is similar in CDM scenario – the CL rate is negative because reduction in DC and A1 countries doubles the reduction in the EU. While theoretically possible, it is likely that DC will behave according to scenario CDMnew rather than CDM. The CDMnew results in an increase of CL rate to 40% due to expansion of emissions in the A1 countries, while by definition, they remain at BAU level in the DC region in this scenario. The difference between the negative CL rate in CDM and positive CL rate in CDMnew is striking. Given the limited precision of CGE models, the absolute level of change should be treated with caution, though the direction of the effect is in line with expectations.

Figure 2. Output in sectors exposed to a risk of carbon leakage, deviation from BAU in %



Note: OIL is not included in EITE.

The CL rate increases from 22% to 28% with the increased EU target (HIGH scenario). This result is comparable with REF scenario only, because other scenarios do not comply with the 'everything else being constant' assumption (see Section 2). When we change several attributes between scenarios, it does not make sense to compare CL. There are two other details that make our definition of CL different from the 'mainstream' literature. We relate CL to LOW scenario, while usually the starting point is BAU scenario. The majority of Annex I countries adopted the Kyoto Protocol, which assumes a low carbon abatement effort, therefore we believe that the LOW scenario is a more appropriate benchmark than BAU for the CL analysis. In particular, the current policy choice for the EU is not between doing nothing or no climate action (BAU) and adopting the 20-20-20 package (REF). Indeed, the choice is between LOW and REF, or between REF and HIGH, when the EU adopts unilaterally a more ambitious carbon reduction target for 2020 than the already existing target. If we ignore it, then CL rate becomes negative for all scenarios, therefore we may give a wrong interpretation for policy makers.

The second detail is related to distinction between abating (A) and non-abating (N) regions. With LOW as a benchmark, the countries with less ambitious abatement targets (A1) and the countries with no binding abatement targets (DC) are grouped together because both regions may be a destination for the emissions leaking from the region with more ambitious climate policy (EU). If we ignore it, then A1 is interpreted as one of the regions that undertake some climate action (no matter if it was historically accomplished or planned for the future) and becomes an abating region. In this case the results for CL are similar to our definition for most of scenarios. The problem arises in scenarios with Clean Development Mechanism. If A1 is interpreted as an abating region, then CDM scenario creates a huge carbon leakage. Such a result is difficult to accept, because the idea of CDM is to reduce not to increase CL. Also CDM scenario cannot generate higher CL rate than CDMnew scenario according to definitions of these scenarios.

Table 5. Global CO_2 emissions and carbon leakage rate

	BAU	LOW	REF	HIGH	CDM	CDMnew	OBA	BTA
Global emissions [%]								
relative to 1990	175	166	165	164	164	166	165	165
relative to benchmark (2004)	139	132	131	130	130	132	131	131
relative to BAU (2020)	100	95	94	93	93	95	94	94
relative to LOW (2020)	105	100	99	98	98	100	99	99
Leakage rate [%]								
relative to LOW where Region A = EU (our definition)			22	28	-200	40	19	-16
relative to BAU where Region A = EU (wrong definition)		-368	-177	-107	-306	-218	-181	-195
relative to LOW where Region A = EU+A1 (wrong definition)			22	28	503	181	19	-16
relative to BAU where Region A = EU+A1 (common definition)		14	16	18	-28	0	15	10

Thus our results for CL (the third row in Table 5) are not comparable with the “mainstream” literature. If we apply a common definition (i.e. the baseline scenario is BAU and non-abating region is only DC), then the results will be underestimated in most cases (the last row in Table 5). We get a difference of 4 pp for OBA, 6 pp for REF, 10 pp for HIGH, and 40 pp for CDMnew relative to our definition. When CL is negative, these results are overestimated (scenarios CDM and BTA). These results are comparable with the relevant literature (see Sections 2 and 3), but we maintain that traditional definitions of CL do not show a true picture. For example, scenario BTA allows for only a slightly reduction of CL according to the common definition, but it will eliminate CL according to our definition. The BTA increases production in abating region (then CL goes down), it increases demand for carbon emission while emission target is the same as in REF scenario (then carbon price goes up as shown in Table 4).

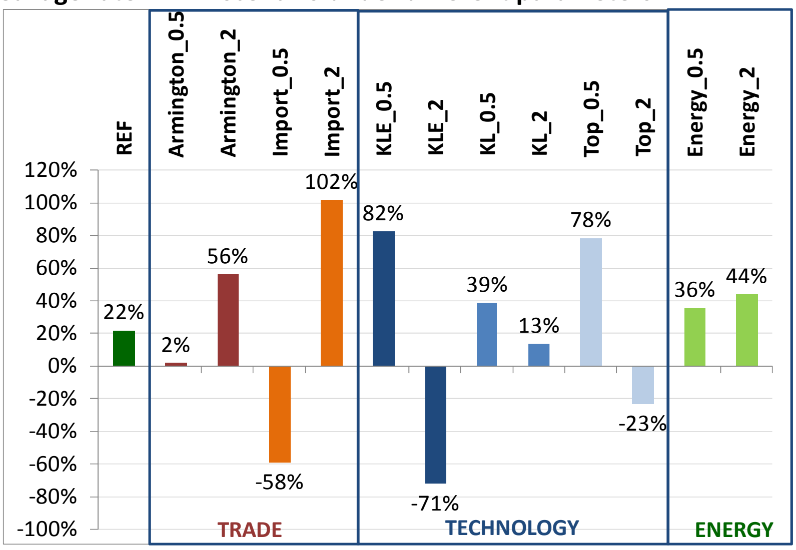
6. Sensitivity analysis

The sensitivity analysis shows that the results generated by CGE models may be assumptions-driven and should be interpreted with caution. In these models, the list of behavioral parameters which determine responses of quantities to changes in relative prices of different inputs is relatively long. As pointed out by Hillberry and Hummels (2012), it is common when calibrating CGE models to select trade elasticities from ‘the literature’. However, there is no clear consensus on which elasticities to use, as elasticities estimated in different econometric studies are far from being uniform. A sensitivity analysis becomes thus crucial.

We compare changes of the carbon leakage rate in the REF scenario (22) while changing parameters used in the ROCA+ model. As a general rule, we divide or multiply the benchmark parameter values by 2. We aim at the identification of those elasticities of substitution in our nested CES production functions[6], which drive the results significantly[7]. We found that only elasticities of substitution in production and trade functions and world price of fuels have a significant influence on CL. In general, these elasticities can be grouped into trade (is the substitution between domestic and foreign goods easy?), technology (how are production factors and their composites combined together?), and energy-specific (is the substitution between different fuels and electricity easy?). We differentiate the latter category from the second one, as the underlying mechanism in the energy sector differs from the general pattern observed for production of non-energy goods (Figure 3). The initial values for trade and production elasticities come from GTAP7 database and Okagawa and Ban (2008), respectively.

A quick look on the results presented below may raise significant concerns, as they suggest that manipulation in the parameters' values change the magnitude of carbon leakage rate and even its direction. This immediately calls for caution in interpreting results of policy analyses, in which these parameters are applied. The benchmark elasticity values, applied in the ROCA+ model, are in line with the best practice of other CGE modelers in the literature. Initial values for energy elasticities are in the range from 0.25 to 1, technology elasticities - from 0 to 1.57, and trade elasticities - from 1.9 to 10 (or to infinity for fuels) as they are presented in Figures 6-8 in the Appendix. The values were taken directly from the original model ROCA.

Figure 3. Carbon leakage rate in REF scenario under different parameters



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[6] A general form of a CES production function is $X(K,L) = (aK^{\rho} + (1 - a)L^{\rho})^{1/\rho}$ where ρ is the substitution parameter ($-\infty < \rho < 1$), which is related to the elasticity of substitution σ, since $\sigma = 1/(1-\rho)$. There are some special cases of interest: when $\rho \rightarrow -\infty$ (or $\sigma = 0$), CES production function converts into Leontief production function $X(K,L) = \min(aK, (1-a)L)$. When $\rho = 1$ (or $\sigma \rightarrow +\infty$), then inputs are perfect substitutes in production $X = aK + (1 - a)L$. When $\rho = 0$ (or $\sigma = 1$), then CES production function converts into the Cobb-Douglas case $X(K,L) = K^{a} L^{1-a}$.

[7] The manipulations in these parameters result also in changes in the BAU scenario, as the model is recalibrated to the new parameters' values. It means that the effective carbon abatement, measured relative to BAU, may change. Nonetheless, the carbon reduction targets expressed as a percentage change relative to 1990 (and a corresponding change relative to the base year in our model), remain unchanged.

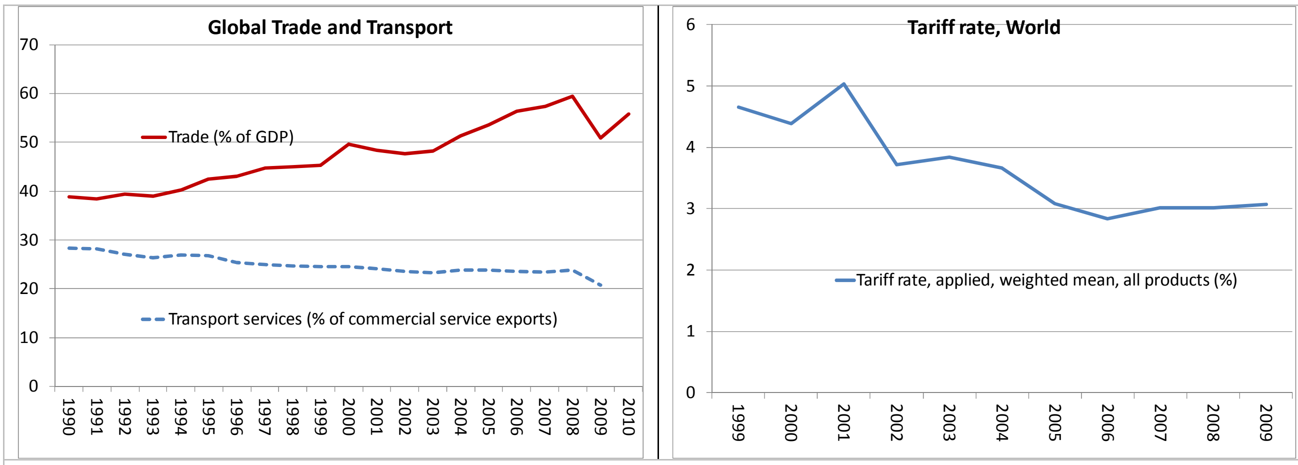
Note: The names of technology parameters refer to different production factors or their composites and come from K- capital, L – labor, and E – energy. Parameter "Top" refers to the top nest in the production function and a substitution between KLE composite and materials. See Figures 6-8 in Appendix.

Despite the above caveat, we observe some consistent patterns in our results. First, higher trade elasticities lead to higher CL rate: import elasticity between different regions (the degree substitution between imports from different regions) drives the results more than the Armington elasticity (the degree of substitution between domestic and foreign commodities). When the elasticities are close to zero, then the substitution possibility is limited. Smaller import elasticity eliminates CL fully (-58), while its doubling fully offsets the reduction efforts in other regions (102). The mechanism is pretty straightforward: an increase of this parameter translates into higher imports from DC, and expanding output in DC leads to higher emissions there.

These observations raise serious questions about the effectivness of unilateral climate action, as ongoing globalization processes suggest that these parameters are (will be) rather higher than lower. Both Armington and import elasticities inform about the degree of difficulty in substitution between domestic and foreign goods (composites) or between goods from different regions. Higher values imply higher homogeneity between these substitutes, i.e. easier substitution. In recent years, there are several factors which support the notion of increasing homogeneity (higher substitution) between tradable goods from different regions over time. The following factors speak in favor of higher homogeneity: rising share of global trade in global output, declining transport costs compared to the traded volumes (Figure 4), a decline in effective import tariff rates (Figure 5), and more widespread regional or global standardization required for many goods.

Second, the higher technology elasticicities, the lower CL rate with a possible change in its sign. It is the opposite relationship than for trade elasticities. Easier substitution between production factors or their composites translates into lower carbon leakage. These effects are higher for a substitution between a capital-labor composite with energy (KLE), and for the top nest, in which a composite good KLE is combined with materials, than for Armington elasticity. In both cases, carbon leakage disappears if the parameter value is doubled, or carbon leakage offsets about 80 of emissions reduced elsewhere. The difference in the results for doubled parameter values (-71 and -23) appears since the assumption of zero initial values for some sectors in the KLE composite (Figure 6) and no such assumption for the top nest. The results are less sensitive to a substitution between capital and labor (KL), though the changes can be regarded as significant.

Figure 4. Global trade and transport trends	**Figure 5. Import tariff rate**



Source: Authors' calculations based on World Development Indicators (2011).

Finally, the interpretation of the sensitivity results for energy-specific elasticities is the most complicated one as for both lower and higher values of these parameters, CL rate grows. The mechanism for a lower elasticity is similar to the case with other technology elasticities – the more difficult substitution between fuels or between fuels' composite and electricity, the more products need to be imported, hence pollution outsourcing is more prevalent. However, an increase in the CL rate observed when doubling this parameter is associated with U-shaped emissions path in the DC countries, with the minimum level close to the benchmark value of this parameter. Environmental Kuznets Curve studies can be referred to in order to explain this non-linearity (Dutt 2009). Perhaps for very high levels of GDP per capita in countries where the carbon 'leaks to', the level of emissions will be low again, but this is clearly much beyond what can be empirically observed now.

In our study, emission change decomposition using LMDI method is helpful in explaining the U-shaped emissions path in DC, and hence rising CL rate both at lower and higher values of elasticities of substitution between fuels and electricity. In low elasticities case, fuel substitution is more difficult, the carbon abatement policy of the Annex I countries translates into a strong rise in electricity prices and higher production costs in EITE sectors. Global prices of coal decline, but the use of coal is not cheap in the Annex I countries. This, in turn, has a large impact on production structure in all regions: a switch towards less energy-intensive sectors like services in the EU and A1, and towards more energy-intensive sectors in DC, based on cheaper fuels. As a result, emissions in DC rise. In high elasticities case, the switch from coal to less carbon-intensive fuels is even faster in A1 and EU. This makes gas and oil much more expensive than coal for DC. Demand for coal increases, and this inevitably leads to higher emissions in DC countries.

7. Conclusions

After a careful review of existing definitions of carbon leakage, we provided a definition with the emphasis on what needs to be kept constant, and applied it in a computable general equilibrium framework for the unilateral carbon abatement commitments by the EU in 2020. Our definition of the CL differs from the relevant literature in several ways. First, we show that not all countries that undertake some climate action are qualified as an abating region. A proper distinction between countries qualified as abating and non-abating regions is essential, because the results for CL will be overestimated when a non-abating region is qualified as an abating one (see the rows 3 and 5 in Table 5). Second, when several assumptions between scenarios are changed, it is hard to find out which one causes a change in CL. Thus, the necessary requirement is the 'everything else being constant' assumption. Third, a BAU scenario with no climate action cannot represent a baseline to define CL because some regions already undertook some climate action; otherwise the results for CL may be underestimated. Fourth, our definition does not involve triggering the implementation of a mitigation policy in regions where the carbon emissions "leak to". The basic assumption is that policies in non-abated regions are kept constant. Changes in those regions occur through general equilibrium effects subject to policy instruments adopted in abating regions, but no simultaneous exogenous changes in the policy in non-abating regions should be considered. This means that existing literature underestimate carbon leakage, since it use less rigorous definition.

Unilateral carbon abatement policies can be counter-productive, as a large part of emissions reduced in the EU or other Annex I countries may be offset by an increase in emissions in the rest of the world. Our policy simulations suggest that more stringent abatement commitments by the EU not only lead to a higher carbon leakage rate, but also translate into higher welfare or output losses for all regions, and the EU in particular. The welfare effects for the latter can be mitigated by anti-leakage measures (OBA or BTA), but this is rather a zero-sum game if the corresponding effects in DC region are considered. International carbon offsets could be part of a solution if DC countries determine their baseline emissions before the CDM transaction and indeed reduce emissions relative to this BAU level. If real BAU emissions in DC are inflated beforehand, and the CDM only brings them to their actual BAU level, the mechanism is ineffective from the climate perspective. The effectiveness of anti-leakage measures varies considerably. The border tax adjustment on imports can reduce carbon leakage significantly, while output-based allocation of free emission permits to sectors exposed to international competition is less effective. Clean development mechanism -- depending how it is defined -- can either remove or increase carbon leakage.

Climate impacts do not affect mitigation policies (Tubi et al. 2012), but only a global action could result in protecting the global climate, and from this perspective any regional policies prove to be insufficient. Aichele and Felbermayr (2012) and Hassler and Krussel (2012) provide evidence that Kyoto Protocol has had at best no effect on world-wide emissions. While unilateral EU climate policy is ineffective, it is not detrimental for global climate protection (our hypothesis is thus not fully confirmed). According to our BAU scenario (based on the IEA projection) in 2020, the EU will be responsible for only about 11% of global emissions, hence, abstracting from the political effects associated with the leadership role, its unilateral actions are doomed to failure in solving the global problem. But even if the United States decides to participate in the global climate action, as long as emerging economies like China, India, Russia or Brazil do not reduce emissions in absolute terms, there is little chance of meeting global targets for stabilizing the concentration of CO_2 at a level necessary to avoid a serious risk of global warming. Bosello et al. (2003) show that equity in inducing more countries to join a climate coalition does not offset the incentives to free-ride on emission abatement. This problem can be solved by long-run agreements that are renegotiated over time.

Using LMDI approach, we decomposed the change in carbon emissions by region into their four major drivers. The largest emission reduction comes from a change in energy mix (a switch towards less carbon intensive fuels). The activity effect is insignificant[8] for emission change in all analyzed scenarios. Changes in economic structures are also not important for the global emission, but import taxes based on carbon

[8] Lockwood and Thomas (2002) provide a theoretical prove for such behavior. While it may be desirable to move immediately to reduce capacity in an industry to some level, this is not an equilibrium because either firm would prefer to have the other reduce capacity while retaining its own capacity.

content would provoke a structural reallocation of resources in the DC economies towards less carbon intensive sectors. Finally, the intensity effect is another important driver of emission reductions thanks to a shift towards less energy-intensive production technologies. Thus investments can be encouraged by emission quotas, but according to Harstad (2012), investments are larger if negotiated quotas are small.

We have found that the European Commission has efficiently distributed emission limits between ETS and non-ETS sectors for the first commitment period (8), but not for the second one (20 and 30). The marginal abatement cost is considerably higher in non-ETS sectors with 10 target than in ETS sectors with 21 target. This means that the target for ETS should be future increased relative to non-ETS. The PRIMES model simulates carbon price for ETS sectors equal to 25 and 39 EUR 2008 for 8 and 20 reduction, respectively. We obtained 21 and 49 USD 2004 for the scenarios LOW and REF, respectively. These correspond to 17 and 39 EUR 2004, respectively. Taking into account 1 percentage point of inflation rate between 2004 and 2008, our results are thus comparable with those of PRIMES for the second commitment period. A historic average of EU ETS allowance price for the first commitment period is about USD 20, but it is USD 9 currently. Hence our estimation is closer to reality than that of PRIMES did.

We have provided evidence that the results crucially depend on technical assumptions and some parameters affect not only the magnitude but even the sign of carbon leakage rate. In other words, depending on these parameters, carbon emissions in the rest of the world either increase or decrease in reaction to the unilateral climate action by the EU. CGE models are powerful tools for policy analyses, but their results require a careful validation of underlying technical assumptions. The PRIMES is a partial equilibrium model, but its details are hidden. Technical assumptions adopted in such models are of critical importance for results of policy simulations. In the sensitivity analysis, we identified a list of parameters (like import or Armington elasticities) which affect not only the magnitude but also the sign of carbon leakage rate. Manipulating elasticities of substitution in production and trade functions suggests that in reaction to the unilateral action of the EU, the remaining countries may either increase or decrease their carbon emissions. Therefore, a careful validation of these assumptions is necessary before policy simulations may support the so-called evidence-based policy recommendations. Nonetheless, we remain strongly positive about CGE models applied in this field provided that underlying assumptions are presented transparently and well explained. Our model can be improved in the future by implementing non-zero carbon price in the benchmark equilibrium and by converting into a fully dynamic version.

Appendix. Illustration of production and trade in the ROCA+ model

Sets:
g – producers and goods (also set *i*),
r – regions (EU, A1, DC),

Variables:
$A_{g,r}$ ($A_{i,r}$) – Armington composite of domestic and imported good (other than ELE, COL, OIL and GAS) used for consumption (intermediate and final);
$M_{g,r}$ – composite of imported good;
$D_{g,r}$ – production for domestic use;
$X_{g,r}$ – production for export;
$Y_{g,r}$ – total production of good;
K_r – capital (region specific);
L_r – labor (region specific);
$R_{g,r}$ – resource rent (only for sectors COL, CRU, GAS, OTH);
ELE_r, COL_r, OIL_r, GAS_r – energy goods;
CO2 – emission from using fossil fuels.

Production of goods: Each unit of fossil fuels (coal, oil and gas) used by producer in activity *g* and region *r*, generates fixed amount of CO2 emissions. Starting from the bottom of the Figure 6 we have oil (OIL) vs. gas (GAS) substitution. On the higher level, a composite of these two fuels might be substituted by coal (COL). Next, a primary energy composite might be substituted by electricity (ELE) and then (in the higher nest) energy might be replaced by mix of capital (K), labor (L) and resources (R). Non-energy goods ($A_{g,r}$) are aggregated in esub_m nest and can be substituted by composite of the previously described aggregate of goods and factors. This set of nests describes the production of good $Y_{g,r}$.

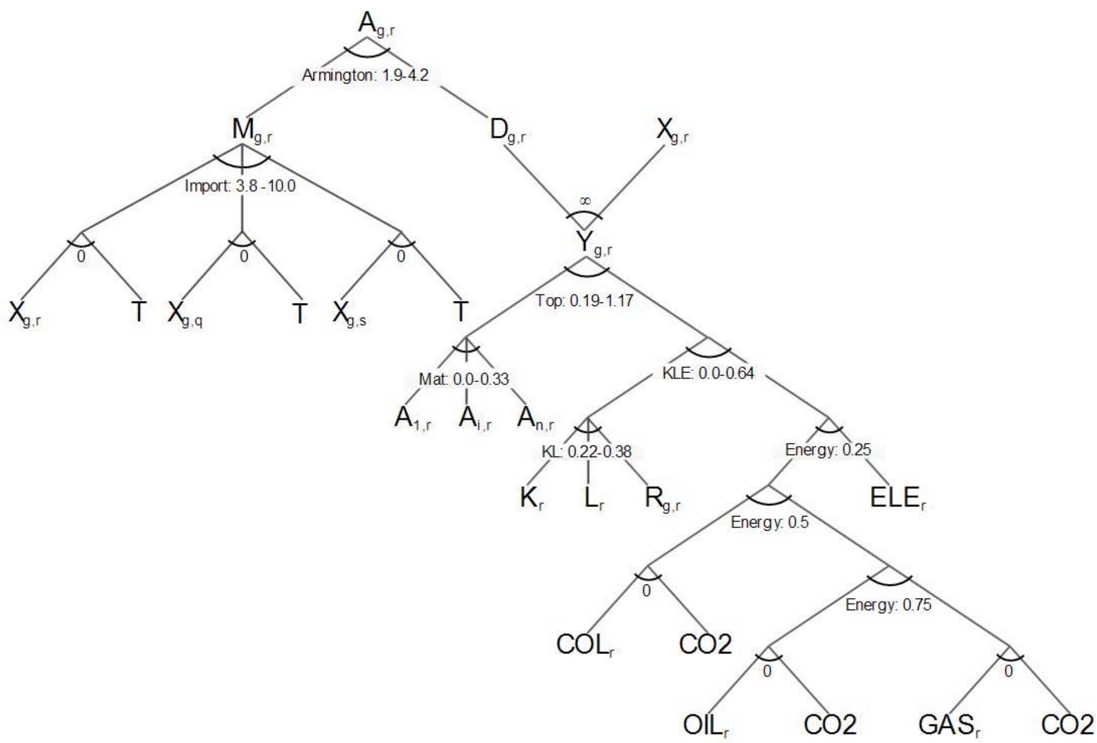
Import and export of goods: In current version of the ROCA model (ROCA+) we have three regions (EU - European Union, A1 - rest of Annex I countries, and DC - developing countries). Production in a given region ($Y_{g,r}$) might be used domestically ($D_{g,r}$) or might be exported ($X_{g,r}$). The model assumes a perfect elasticity of transformation between the two (domestic and foreign) markets. Export from other two regions $X_{g,q}$ and $X_{g,s}$ is at the same time import to region *r* (as shown in Figure 6-8). A part of *r* region export $X_{g,r}$ also goes as import to the same region in order to account for trade between countries within a given region. Each imported good has two fixed international transport margins T (aviation and other). Mix of composite of imported goods $M_{g,r}$ and domestic production $D_{g,r}$ leads to Armington composite $A_{g,r}$.

Description of elasticities of substitution as shown on Figures 6-8 Error! Reference source not found.

Armington	Armington elasticities of substitution;
Import	elasticities between imports from different regions;
Top	elasticity of substitution between materials composite and energy goods-value added composite;
KLE	elasticity of substitution between value added and energy goods;
KL	elasticity of substitution between capital, labor and resources;
Energy	elasticities of substitution between energy goods;
Mat	elasticity of substitution between material goods.

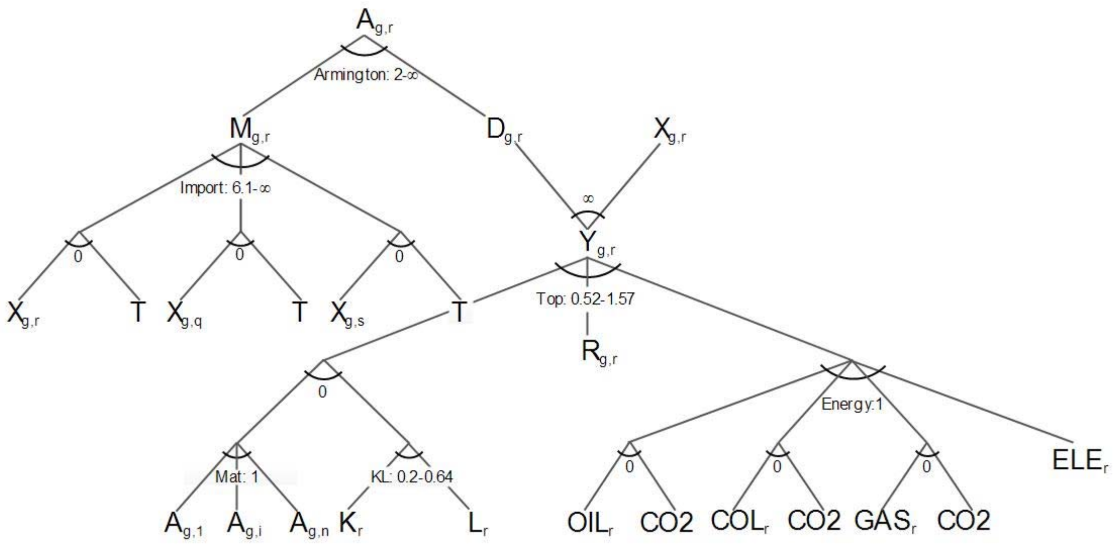
Numbers in the graphs show initial (before sensitivity analysis) value ranges by sectors of the elasticities of substitution. The values come from the ROCA model.

Figure 6. Production and trade structure for commodities other than energy



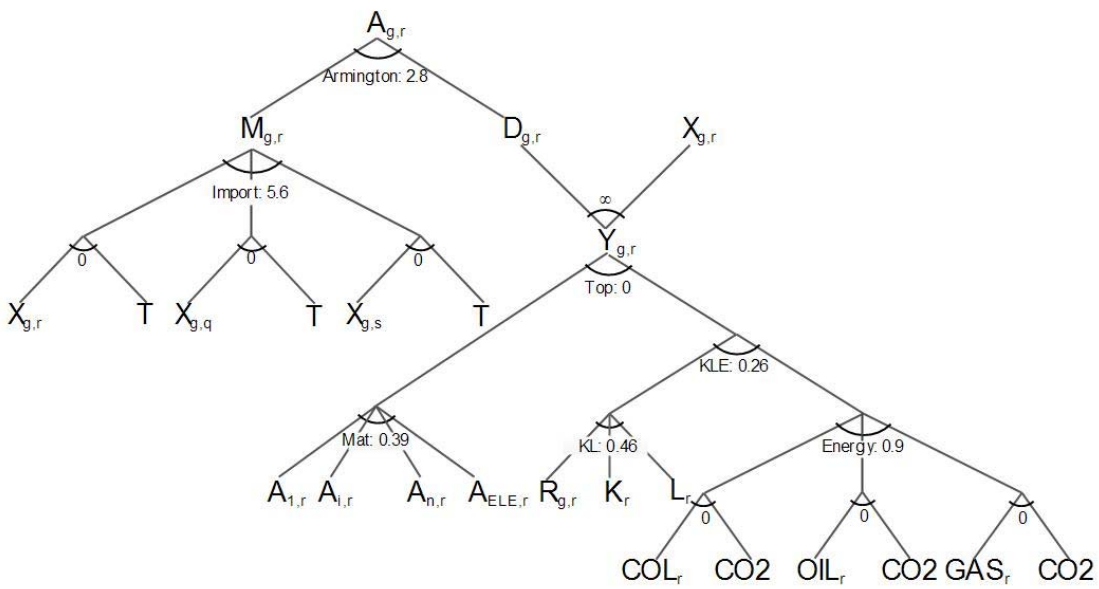
Source: ROCA model

Figure 7. Production and trade structure for fossil fuels (coal, crude oil, and gas)



Source: ROCA model

Figure 8. Production and trade structure for electricity



Source: ROCA model

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