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Analysis of Climate Policies with GDyn-E

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By Alla Golub

Abstract

This paper documents GDyn-E CGE model developed for analysis of climate policies in dynamic GTAP framework. Description of the modeling framework is followed by a presentation of a simple application focused on emission leakage associated with a unilateral GHG abatement policy, analysis and decomposition of the emission leakage, and sensitivity analysis.[1]

JEL Classification: D58, Q58, F18

Keywords: unilateral climate policy, carbon leakage, dynamics

[1] Appendix D lists experiments included in the version archive of GDyn-E model application accompanying this paper.

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1. Motivation

A key element of the current debate over climate policy in the US is that of competitiveness. If the US undertakes legislation that raises energy costs, it is likely that energy intensive industries in the US will lose competitiveness, unless other countries also undertake similar measures. It is commonly referred to as the leakage question, since abatement in one region may give rise to the shifting of emissions intensive production to other regions, thereby diluting the global abatement achieved.

Computable General Equilibrium (CGE) models have been widely used to analyze the question of leakage, as they are explicitly designed to capture the impact of policies on the relative competitiveness of sectors/regions of the global economy. Buriaux (2001) compares estimates of leakage associated with the implementation of the Kyoto Protocol reported in earlier studies and find them in a range "from around 20 per cent in WorldScan, MERGE and Rutherford's models to the lower bound estimates of 2 to 5 per cent provided by the GREEN, G-cubed and EPPA-MIT models." In recent study, Bohringer et al. (2012) summarizes results of the Energy Modeling Forum model comparison study (EMF 29) on the efficiency of border carbon tax adjustments in carbon leakage reduction. The study builds on model-based analysis of twelve expert groups that jointly investigate a set of pre-defined policy scenarios with harmonized assumptions and a common dataset. In the reference scenario when Annex I regions reduce emissions by 20% relative to 2004 level, leakage rates range between 5% and 19% with a mean value across all models of 12%.

To date, most CGE models have focused on leakage through a trade channel, e.g. US climate policy results in higher priced exports, which are displaced by exports from non-participating economies. At the same time, import penetration in the US market by these same economies rises as their products become more competitive. The trade leakage effect is expected to dominate in the short run. However, over the longer run, we expect climate/energy policies to affect investment incentives and hence the flow of capital across borders. This second channel is termed *investment leakage*. It has been more difficult to quantify due to uncertainty about capital mobility. The few studies that have looked at changes in competitiveness and carbon leakages generated by the reallocation of capital incorporate capital mobility under very restrictive assumptions, choosing either perfect capital mobility or no capital mobility. This ignores the empirical evidence of imperfect capital mobility.

This paper documents a multi-sector multi-region recursive dynamic applied general equilibrium model GDyn-E. The feature that makes this model especially suitable for the analysis of investment leakage is its disequilibrium mechanism for determining the regional supply of investments, which is critical for analysis of carbon leakages due to climate policies. The analysis presented here is influenced by work of Jean-Mark Burniaux (2001), who used earlier version of GDyn-E model to analyze emission leakage associated with Kyoto protocol.

The paper is organized into 7 sections. Modeling framework is described in section 2. Section 3 presents baseline assumptions and simple policy scenario. Investment theory of the model and the leakage mechanism are described in section 4. Leakage rate results and decomposition are presented in section 5. Sensitivity of the results to alternative technology parameters specification is presented in section 6. Summary and future model improvements are outlined in section 7.

2. Modeling Framework

The GDyn-E model is a multi-sector, multi-region, recursive dynamic applied general equilibrium model. It provides a time path of the global economy and CO_2 emissions, and allows analysis of GHG mitigation policies differently affecting gross domestic product and gross national product, and incentives to invest in different regions. The model represents the merger of a dynamic CGE model suitable for long term projections and a static CGE model developed for energy and environmental policy analysis with focus on the energy substitution in production and consumption, carbon dioxide emissions from fossil fuel combustion, and emission trading. The first model is modified version of the dynamic GTAP model GDyn (Ianchovichina and McDougall, 2001). The second model is the GTAP-E model documented in Burniaux and Troung (2002) and further technically improved in McDougall and Golub (2007).

2.1 Theoretical Structure of GDyn-E

The GDyn-E model incorporates *all* elements of the GDyn model theoretical structure (Ianchovichina and McDougall, 2001), including treatment of time as a variable, capital accumulation, stylized representation of financial assets and associated income flows, and investment theory. These important elements are briefly described below. Interested reader is referred to Ianchovichina and McDougall (2001) for detailed exposition of the GDyn theoretical structure. Detailed information on GDyn data base construction and parameterization of the model, as well as various applications of GDyn model are available in Ianchovichina and Walmsley (2012).

The feature that distinguishes the GDyn-based model from other dynamic CGE models is its disequilibrium approach to modeling capital mobility. The approach allows short and medium run differences in the rates of return which, if desired, are eliminated in the long run.[2] That is, there is imperfect capital mobility between regions in the short to medium run and perfect capital mobility between regions in the long run.

The treatment of financial assets in the model is "minimalist and highly stylized" (Ianchovichina and McDougall, 2001) and driven by the goal to represent international capital mobility "without creating leaks in the foreign accounts," rather than depict financial sector realistically. Of many classes of finical assets that exist in real world, the model includes just one asset class, equity. This financial asset represents indirect claim to only one physical asset – physical capital.[3] In the model, firms own physical capital, but rent land and natural resources from regional households. Regional households, on the other hand, "own land and natural resources, which they lease to firms, and financial assets, which may be construed as indirect claims on physical capital" (Ianchovichina and McDougall, 2001).

With capital internationally mobile, regional households could hold equity in firms in all regions. This implementation, however, would require bilateral data on foreign assets and liabilities. To minimize data requirements, Ianchovichina and McDougall (2001) implemented the fiction of a global trust that serves as a financial intermediary for all foreign investment. Regional households do not hold equity directly in foreign firms, but only in local firms and the global trust.

[2] GDyn allows to model risk premia. If risk premia persist in the long run, then short and medium run differences in the rates of return are eliminated not completely, but up to imposed risk premia.

[3] Alternative implementation may include land and natural resources in the set of physical assets that back financial assets.

Thus, total financial wealth of the regional household consists of equity in local firms and equity in global trust (see Ianchovichina and McDougall (2001) for further details).

In the model, investors respond to expected rates of return when making decisions about how much to invest. The model allows for errors in investors' expectations so that the model can match up with real world cases where currently observed rates of return are apparently inconsistent with current levels of investment. For example, when investment is high despite low observed rates of return, errors in expectations are incorporated allowing expected rates of return to exceed actual rates. Over time investors adjust their expectations to eliminate errors in expectations and expected rates of return move towards actual rates.

Investment in each region in each period is determined by investors' expectations about the rates of return as well as the constraint that global investment must equal global savings. The global trust, a financial intermediary for all foreign investment, distributes funds among regions according to investors' expectations, while respecting the global constraint. The funds are distributed between regions so that capital moves gradually from regions with lower expected rates of return to regions with higher expected rates of returns, driving the expected rates of return down. At the same time, the expected rates of return move closer to the actual rates of return over time, as errors in expectations are eliminated. These two mechanisms lead to the equalization of expected and actual net risk adjusted rates of return within and across regions, in the long run.

The rates of return convergence mechanism in the model is parameterized based on econometric work of Golub (2006). Golub (2006) constructed the rates of return to capital to test the hypothesis of the convergence in rates of return across countries and to measure the degree of international capital mobility. Based on econometric analysis, the null hypothesis of no convergence was rejected. The speed of convergence in net rates of return to capital in 20 OECD countries was estimated to be 9% per year. The convergence mechanism in the model is parameterized to mimic the observed degree of capital mobility.[4]

Regional investments include both domestic investment and foreign investment via the global trust. Savings of the regional household, in turn, are spent on investment in the domestic economy and investments in the global trust. Period by period decisions about the investments and savings composition affect the composition of capital and allocation of wealth of a region. Golub (2006) estimated the parameters determining relative rigidities of composition of capital and allocation of wealth in the model using country portfolios data base documented in Kraay et al. (2000). While there are differences in the relative rigidities of the composition of capital and allocation of wealth across countries, in the majority of countries the split between capital belonging to foreigners and capital belonging to local households is much more rigid than the split between equity in local firms and equity in foreign firms. The results of the econometric investigation are used to set the rigidity parameters in GDyn-E.

In the standard specification of the dynamic GTAP model (Ianchovichina and McDougall, 2001), as well as in static GTAP model (Hertel, 1997) savings is a fixed proportion of income in

[4] Note that the convergence rate of 9% per year was obtained using OECD data only. Most likely, the speed of convergence would be lower if econometric investigation included countries outside OECD, and hence a speed of convergence of 9% per year represents the upper bound of the desirable convergence of the net rates of return in the model.

each region.[5] There are two unwelcome implications of this. First, net foreign positions grow without bound in GDyn simulations. The second problem is that as economies with high savings rates, like China, grow, there is a glut of global savings and, as a result, of investment and capital in the world. Because of excessive investment, rates of return to capital fall without bound. Golub and McDougall (2012) developed new specification of household saving behavior. In the new specification, the saving rate in each region of the model is endogenous and is a function of the ratio of wealth to income. New theoretical structure supports balanced growth scenarios, stabilizes global rate of return to capital, and prevents net external assets or liabilities from growing implausibly large. The user of GDyn-E is offered choice between standard GTAP specification of savings and the new household savings behavior. This option is available through closure swap (see Appendix A for details).

Production and consumption sides of the new model, emissions accounting, emissions taxation and emissions trading of GDyn-E are inherited from GTAP-E model. Theoretical structure of these GTAP-E elements incorporated into GDyn-E model is described in details in GTAP Technical Paper 16 by Burniaux and Truong (2002) and GTAP Research Memorandum (RM) 15 by McDougall and Golub (2007). Most important features are briefly described below. Interested reader is referred to McDougall and Golub (2007) for detailed representation of new variables and equations. Some differences between GTAP RM 15 and GDyn-E technical implementation are listed in Appendix B.

The GDyn-E model tracks CO_2 emissions by agent and source (imported or domestic) and assumes that emissions are proportional to emitting input use by firms or emitting commodity consumption by households.[6] Two instruments are available to control emissions in each region of the model: carbon tax and emission constraint represented by emissions quota variable. With emission trading, regions' actual emissions and emission quota may diverge, and the difference between the two represents permits purchased from or sold to other regions. To represent emission trading, the world is divided into *blocs* of regions trading emission permits amongst themselves; a non-trading region is just a one-region bloc. With no trading, the set BLOC of blocs is just the set of regions; with Annex I trading, the Annex I regions form one bloc together, and the non-Annex I regions form blocs individually. A mapping REGTOBLOC shows which regions belong to which blocs. The set BLOC and the region-to-bloc mapping are recorded in the sets file.

Production and consumption structures of GDyn-E differ from GDyn and the standard static GTAP model (Hertel, 1997). The supply side of this model follows GTAP-E production structure represented by constant returns to scale, nested CES functions, which first combine primary factors into composite value-added-energy, and imported and domestic non-energy intermediate inputs into composite intermediates, before aggregating these composites into an aggregate output. Important distinction between GDyn-E/GTAP-E and standard GTAP model production structures is that the former incorporates the substitution possibilities between alternative fuels (inter-fuel substitution) and between the energy aggregate and other primary factors, such as capital and labor (fuel-factor substitution). To implement this system, a new set

[5] In fact, the propensity to save is not quite fixed; see McDougall (2002). But it is close enough to fixed for the present purpose.

[6] The current version of the model only considers carbon dioxide emissions from fossil fuel combustion by industries and households. Other GHG gases (methane, nitrous oxide and fluorinated gases) and forest carbon sequestration are not included in this version of the model.

SUBF_COMM of subproducts corresponding to various composites within the production structure (value-added-energy composite, capital-energy composite, and so on) is defined. Subproducts, endowments and tradables are included in a set FIRM_COMM of commodities demanded by firms. The old variables qf and pf, ranging over tradables, are renamed into qft and pft, and old names qf and pf are used for variables ranging over FIRM_COMM. The old variable af representing tradable-input-saving technological change, along with afe for endowment-saving and ava for value-added-saving technological change, is replaced by a new af variable ranging over FIRM_COMM, enabling us to simulate technological change at every point in the production system (see McDougal and Golub (2007) for further details).

The base case production structure of GDyn-E model is parameterized in the following way. The elasticity of substitution in value-added-energy composite is set as in the standard GTAP model, except for gas, coal and oil sectors. In these sectors the elasticity is calibrated to mimic supply response documented in Burniaux (2001).[7] Capital –energy and inter-fuel substitution parameters are taken from Burniaux and Truong (2002). Alternative parameters specification suggested in Beckman et al. (2011) and sensitivity of the results with respect to parameterization of the production structure are considered below.

Private and government consumption systems of GDyn-E follow the structure proposed by Burniaux and Truong (2002). To implement them, new sets of subutilities SUBP_COMM and SUBG_COMM are defined and included with tradables in sets PRIV_COMM and GOV_COMM, respectively. As in standard GTAP, top level private household expenditure system is a Constant Difference of Elasticity (CDE) expenditure function. The top level of government consumption system is represented by CES with elasticity of substitution set to 0.5 (Burniaux and Truong, 2002). Energy commodities are bundled together into energy subutility specified as a CES sub-structure with elasticity of substitution equal to 1 in both private and government consumption (Burnioux and Troung, 2002). This energy bundle competes with all other non-energy consumption goods within the CDE structure in private consumption. In government consumption, the energy bundle competes with non-energy commodity bundle within the CES structure.

3. Baseline Assumptions and Illustrative Scenario

The starting point of our simulation is the world economy in 2004, as depicted in the GDyn v.7 data base. 21 sector and 20 region aggregation of GDyn version 7 data base is employed in this analysis (see Appendix Table C1 and C2 for region and sector definition and mapping to GTAP standard sectors and regions). In the baseline (and policy) simulations from 2004 to 2020, labor force and population are all exogenous to the model. Historical and projected population and labor force (skilled and unskilled labor) growth rates for 2004 – 2020 are taken from Chappuis *et al*. (2011).

Historical real GDP growth rates are taken from Chappuis *et al*. (2011). The real GDP path for 2012 − 2020 is driven by assumptions about economy-wide productivity growth in non-accumulable endowments, presented in column 3 of Table 1.[8] Resulted cumulative GDP growth

[7] The target supply elasticities are 4 for gas, 1 for oil and 10 for coal.
[8] The model is equipped with a mechanism that allows incorporation of sector productivity differentials. A coefficient DIFF is introduced into equation AEWORLD determining sector/region/input specific rate of input augmenting tech change. Coefficient DIFF is read from the parameters file. The default is unity corresponding to

rates are shown in column 7. Fastest GDP growth is achieved by China, closely followed by India. The assumed productivity growth rate in China is higher than in India to respect recent historical development of GDP growth rates in these countries. However, due to slowdown in China's labor force growth and continued strong growth of labor supply in India, by 2020 India is catching up to China by the cumulative GDP growth.

Another important aspect of the baseline is the change in efficiency of energy use, known as autonomous energy efficiency improvement rate (AEEI). AEEI represents the rate of change in the input coefficients for energy or fossil fuels due to the evolution of non-price induced, technologically driven changes in energy demand. In GDyn-E, AEEIs are modeled with fossil fuel and electricity input-saving technical change. Assumptions about the magnitude of the technological change in each sector and region are influenced by Paltsev et al. (2005). Specifically, in developed countries and China, 1%/year technological improvement is applied to gas, coal, oil, oil products and electricity inputs used in non-energy sectors; 0.5%/year technological improvement is applied to gas, coal, oil, and refined petroleum inputs used in the electricity sector. No improvement in energy use is assumed in gas, coal, oil, and refined petroleum sectors. No change in efficiency of energy use is assumed in developing regions other than China.[9]

The environmental effectiveness of unilateral policies like Kyoto could be reduced by increased emission levels in countries not committed to reduce emissions, the effect called "carbon leakage". To quantify the carbon leakage, Annex I emission reduction scenario is analyzed with GDyn-E model. Eight of twenty regions in the aggregation are Annex I regions. For these regions, exogenous shocks to emissions are constructed in accordance with Copenhagen commitments (UN FCCC, March 10, 2011). Annex I regional emission reduction targets converted to equal annual shocks are presented in Table 2. These shocks are applied from 2004 to 2020.

4. GDyn Investment Theory and Leakage Mechanism

The purpose of the GDyn-E investment theory is to determine how much should be invested in each region in each period during the simulation. Consider the impact of GHG mitigation policy on the rental price of capital. Because capital and emissions are more or less complements, GHG mitigation policy will reduce the rental price and rate of return to capital in the regions implementing policy, creating profitable opportunities in the countries that do not implement emission cuts. As a result, investors will reallocate capital from countries with relatively lower rates of return to countries where rates of return are expected to be higher. In a model with perfect capital mobility, profit-maximizing investors would reallocate their investment instantly so that the rates of return across countries would remain equal. This mechanism, however will lead to unrealistically high volatility in the price of capital goods and in the level of investment because the model does not capture real world features such as gestation lags, adjustment costs and capital gains, and typically assumes perfect capital mobility across sectors within a region. For these reasons, the perfect adjustment approach is unrealistic in the context of this model and a lagged adjustment approach is deployed (Ianchovichina and McDougall, 2001).

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uniform productivity improvement across sectors. This assumption can be modified to reflect sectoral differences in productivity growth.

[9] The implementation of AEEIs in this paper departs from Paltsev et al. (2005), which assumes reduction in the efficiency of energy use between 1997 and 2030 in developing countries, excluding China.

The lagged adjustment approach to modeling international capital mobility allows gradual capital reallocation from regions with lower rates of return -- these are countries that implement climate change mitigation policies -- to countries that do not have such policies in place and where returns are expected to be relatively higher. The disequilibrium approach permits analysis of the effects of gradual capital reallocation induced by GHG mitigation policy on the regional economic growth and GHG emissions.

The GDyn-E investment theory is based on three rates of return concepts: target, actual and expected rates of return. The target rate of return is the rate of return which equalizes global savings and investment.[10] As global savings and investment change over time, so does the target rate of return. This global rate of return is the rate of return that all regions in the model are converging to in the long run in the absence of risk premia. The actual rates of return reflect actual profitability of regional capital stock. Investors in the model react to expected rates of return to capital, not to actual rates of return, and behave such that differences between expected rates of return and the target rate of return are gradually eliminated over time. In the model, the profit maximizing behavior of investors is represented by a downward sloping relationship between the rate of return and the capital stock: the marginal product of capital is falling as more capital is accumulated (Figure 1).

The disequilibrium approach is based on three lagged adjustment mechanisms. Let us consider a region where expected rate of return is above target rate, but below actual profitability of capital in that region. First, investors gradually reallocate funds such that expected rate of return move toward target rate. This is shown by arrow (1) in Figure 2. In this illustrative example, the expected by investors rate of return is higher than the target rate. In this case investors will invest more in this specific region to increase its capital stock and move close to the target (global average) rate of return. Second, investors detect errors in their expectations (these are differences between expected and actual rates of return to capital), and gradually adjust their expectations to move them close to actual rates of return (arrow (2) in Figure 2). Finally, investors allow for some normal rate of growth in the capital stock, where normal rate is a rate at which regional capital can grow without affecting returns to capital. This normal rate too is an estimated (perceived) rate that investors adjust through time. So, if investors observe positive growth in rates of return, they revise their estimate of normal rate of growth in capital stock upward. This will lead to outward shift of their expected investment schedule in the direction of the actual (warranted) rate of return schedule (arrow (3) in Figure 2). In the long run, the model converges towards a stable equilibrium where the actual and expected investment schedules coincide and the target, expected and actual rates of return are equal.

Burniaux (2001) analyzes carbon leakage due to international capital reallocation using the earlier version of GDyn-E model and describes how abatement of CO_2 emissions by a typical Annex I country will affect the investment decisions in Annex I and non-Annex I countries. To simplify this illustrative example, we focus on two aggregated regions – Annex I and non-Annex I. Further, we assume initial equality between the regional actual and expected rates of return, and target rate of return. This equality implies that the actual and expected rate of return schedules overlap and move together in response to changes in the normal rate of growth in the capital stock. Because **c**apital and energy are more or less complementary, the emission reduction in Annex I

[10] In the GDyn data base, target rate of return is calculated as a ratio of global earnings to capital to the global value of capital (see McDougall et al. 2012).

leads to reduction in actual rates of return to capital in these regions. Investors detect economic slowdown and revise their perceived normal rate of growth in capital stock downward, which leads to reduction in investments. The investors expected schedule moves inward (arrow (3) in Figure 3). In the same time investors realize that the expected rate of return is now higher than the actual rate of return. Investors detect differences between expected and actual rates of return and gradually revise their expectation downward. As a result, the expected schedule shifts downward (arrow (2) in Figure 3). The reduction in Annex I rates of return to capital causes the global (target) rate of return to fall. However, because Annex I represent only part of global economy, the percentage change reduction in the target rate will be smaller than reduction in Annex I rate of return. Thus, after investors revise their expectations, they realize that expected rate of return in Annex I is below the target rate. This translates to leftward movement along the rate of return schedule leading to further reduction in capital in Annex I (arrow 1 in Figure 3). Thus, Annex I GHG mitigation policy results in lower level of investment and capital in that region.[11]

Now let us turn to non-Annex I case. Figure 2 is useful to demonstrate adjustments in typical non-Annex I country. Annex I emission reduction increases costs of production in Annex I, and improve competitiveness of non-Annex I producers. Moreover, reduction in Annex I fossil fuel use results in decline in fossil fuel international price faced by non-Annex I. Both factors result in the increase in the non-Annex I actual rate of return to capital. Investors detect increase in actual rates of return despite the increased level of the capital stock and revise their perceived normal rate of growth in capital stock up, leading to rightward movement in the expected rate of return schedule (arrow (3) in Figure 2). Investors detect errors in expectations and move the expected rate of return schedule up, toward the actual rate of return curve (arrow (2) in Figure 2).
Finally, when actual rates of return fall in Annex I, the target rate of return falls as well, sending investors signal to revise their expectations about rate of growth in the rate of return in the rest of the world downward. Investors are increasing level of investments in non-Annex I to move rightward along the rate of return schedule toward new (lower) target rate (arrow (1) in Figure 2). In the end, these mechanisms result in increased level of investments and capital in non-Annex I, implying higher economic growth and higher emissions in the non-Annex I countries (Burniaux, 2001). These emissions through international capital reallocation channel are additional to carbon leakage through structural and international energy prices channels.

5. Carbon Leakage Results

Figure 4 shows the evolution of emissions in the baseline and in the illustrative scenario where Annex I countries reduce their emissions between 2004 and 2020. In the baseline global emissions have doubled from 26 $GtCO_2$ in 2004 to 52 $GtCO_2$ in 2020.[12] Largest growth in the emissions relative to the base year is observed in China and India. In the policy scenario, global emissions have increased less – up to 46 $GtCO_2$ in 2020, with Annex I countries reducing and non-Annex I increasing emissions. Cumulative impact of the policy on emissions, relative to baseline, and costs of abatement in 2020 are shown in Table 4. Figure 9 (blue line) shows gradual increase in Annex I carbon taxes over the time horizon of the analysis, indicating that successive reduction

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[11] In this discussion, the lagged adjustment process is broken down into steps. In the model, all these adjustment mechanisms take place gradually and simultaneously.

[12] 2004 GTAP CO_2 emissions from fossil fuel combustion are roughly 26,000 million metric tonnes of CO_2. Other sources report different estimates. For example, Energy Information Administration (EIA) reports 27,463 and IPCC reports 28,130 million metric tonnes of CO_2. GTAP combustion base CO_2 emissions are calculated from the GTAP energy volume data to insure internal consistency between the emission data and energy values and volumes recorded in the GTAP data base. Lee (2008) documents construction of the emission data set.

in emissions can only be achieved only by ever-larger increase in carbon taxes. Note, the model is not equipped with backstop technologies which are critical to the carbon tax result. Presence of the backstop technologies would limit the increase in the carbon taxes.

While emissions are reduced in Annex I regions that implement abatement policies, they increase in other regions (Table 4). The "leakage rate" is defined as the ratio of the additional emissions in the non-Annex I countries to the emission reduction in Annex I countries. The carbon leakage generated by Annex I unilateral abatement is rising from 4% to 14% between 2004 and 2020 (Figure 5a). Twelve non-Annex I countries are grouped into five groups: China, India, Other Asia, Central and South America, and Africa and Middle East. Figure 5a shows contribution of each of 5 groups to total carbon leakage. Initially, Middle East and North Africa region is the largest contributor, which is surpassed by China in later years of the simulation.[13] China's relative contribution to the global leakage is growing, but then growth starts to slow down in the end of the projections period as other non-Annex I economies increase in size and emission levels.

5.1 Decomposition of Carbon Leakage

Burniaux (2001) identifies one energy and two non-energy channels of carbon leakage. Let us consider the energy channel first. Annex I unilateral carbon abatement results in the reduction in global demand for fossil fuels and their international price. As a result, non-Annex I producers increase energy demand and emissions. There are two important factors determining size of the energy channel. First is the supply response of the fossil-fuel producers. If the supply of carbon is inelastic then the carbon leakage will be large. Given that coal is the most carbon-intensive fuel, the supply elasticity of coal should be important for the size of carbon leakages. Second factor related to the size of the energy channel is the degree of technological flexibility of the production function, and, more specifically, inter fuel substitution.

Non-energy channels include structural and investment reallocation channels. The structural channel relates to the increase in production cost of the energy-intensive sectors in abating regions affecting their competitiveness in international markets. In the considered example, Annex I energy-intensive sectors can lose market shares in the international markets in favor of industries located in non-Annex I. As a result, energy-intensive production in non-Annex I expands, as well as emissions. Second non-energy channel is related to the reallocation of capital to non-participating countries. As noted in Burniaux (2001), "…this channel is dynamic in nature, since additional investments in non-participating countries result in higher economic growth, and GHG emissions increase over the future."

To understand the contribution of these channels to the carbon leakage from Annex I unilateral abatement, we follow the decomposition approach outlined in Burniuax (2001). The decomposition method consists of two intermediate simulations used to decompose the leakage into the three channels: structural, international investment reallocation, and international energy prices. Annex I emission reductions in these intermediate scenarios are the same, but changes in non-Annex I emissions differ, which allows to decompose total policy emissions into three channels. This, in turn, allows decomposition of the leakage rate into the three channels. The first

[13] In this scenario Annex I countries meet their emission reductions individually – no trading is allowed among them. With emission trading, the total leakage rate is about 1% smaller by 2020. The comparison of the leakage rates with and without trading is provided in Figure 5b.

intermediate scenario has the same features as the policy scenario (Annex I emission reduction), except that the prices of the primary fossil fuels (coal, crude oil, and natural gas) are kept constant at the same level as in the baseline scenario. The difference between the Annex I emission reduction scenario and the fixed fossil fuel prices scenario allows identifying the amount of leakage that is channeled through the international energy prices.

Second intermediate scenario assumes that both the prices of the primary fossil fuels and the capital stock in each region are kept fixed at the same level as in the baseline scenario. The difference between the "fixed fossil fuels prices" and the "fixed fossil fuel prices, fixed capital" scenarios allows quantifying the impact of the change of the capital stock in each region, as a result of the worldwide investment reallocation, on the emission leakage. Finally the difference between the "fixed fossil fuel prices, fixed capital" and the baseline allows identifying the emission leakage due to the shift of the non-Annex I economy structure towards more carbon-intensive industries.

Figure 6 shows the decomposition of the carbon leakage into the three channels. The largest channel is structural. Over time, in the absence of carbon free energy resources in the model, the investment channel becomes more important. The international energy prices channel is negative initially. The model is parameterized so that supply of coal, the most carbon intensive fossil fuel, is more elastic than the supply of less carbon intensive oil and gas. When a large group of countries reduces consumption of fossil fuels, international prices of oil and gas fall more than the price of coal, and non-Annex I countries take an advantage of these less carbon intensive fuels, which leads to the initial negative emission leakage.

6. Sensitivity Analysis

How sensitive is the carbon leakage to the choice of the production structure parameters? We are interested in the sensitivity of the results with respect to the elasticity of the supply of carbon and technological flexibility.[14] Two sets of parameters are considered. One consists of the original GTAP-E parameters, as documented in Burniaux and Troung (2002). These parameters are similar to the parameter set employed in GREEN GE model (Lee et al. 1994). Another set of parameters comes from Beckman et al (2011) work which undertook some GTAP-E model validation exercise and arrived at very different set of parameters. Beckman et al (2011) focus on a medium run price volatility of crude oil and gasoline. They measure the historical 1980-2005 price volatility of crude oil. Then using information on the non-systematic historical volatility of supply and demand for crude oil they conducted SSA to measure the GTAP-E estimated price volatility of crude oil. Beckman et al. (2011) find GTAP-E oil price volatility too small and conclude that the GTAP-E demand for crude oil and gasoline is too price elastic, and recalibrate parameters of the model using available econometric estimates.

It should be noted that the focus of Beckman et al. (2011) is on crude oil and gasoline because "… as indicated by usage shares, no energy source is more important than petroleum products" (Beckman et al., 2011). However, if we are interested in the carbon leakage, crude oil and gasoline are responsible for about 40% of global GHG emissions from fossil fuels. Other 60%

[14] Sensitivity of the leakage rate with respect to assumptions about AEEI rates is also considered. The base case includes certain assumptions about AEEI rates (see "Baseline assumptions and illustrative scenario" section). The alternative case is when AEEI rates are zeros. That is, energy efficiency does not improve overtime. Emission leakage results are similar in both cases. Emission leakage rises to 15.3% in "without AEEI" case and to 14.4% in "with AEEI" case.

comes from coal and gas. While undertaken validation exercise with focus on supply and demand of crude oil and gasoline is useful to parameterize these sectors for the analysis of biofuel mandates, in the future it is important to implement similar validation exercise with respect to coal and gas.

Another important limitation of using Beckman et al. (2011) parameters in this study is its focus on short- to medium-term time horizon of the analysis. Time horizon considered in this carbon leakage analysis is longer, and Beckman et al. (2011) technological flexibility parameters are likely to be too small for the time horizon considered in this paper. Nevertheless, this alternative specification is useful to demonstrate sensitivity of the carbon leakage to these parameters.

The comparison of two sets of parameters is presented in table 3. Overall, Beckman et al. (2011) parameters are much smaller. Supply elasticities of coal (the most carbon intensive fossil fuel), and oil and gas (less carbon intensive fuels) depend on the elasticities of substitution in value added-energy composite in the production structure of coal, oil and gas sectors, respectively. For the same cost structure, larger elasticity of substitution results in a more elastic supply (easier to move from sector specific factor which is natural resource in the case of coal, oil and gas). Burniaux and Troung (2002) calibrate elasticity in value-added-energy composite of the fossil fuel sectors to mimic the fossil fuel supply response assumed in GREEN. Beckman et al. (2011) also calibrate elasticity in the value-added-energy composite of fossil fuel sectors, but use different targets. They draw on Krichene (2002) estimates of the long-run supply elasticities for crude oil and gas, and Toman et al. (2008) estimates for coal.[15] Comparison of the two sets of supply response of the fossil fuel producers, as well as calibrated elasticities in the value-added composite are presented in Table 3. In both sets, the coal supply is more price elastic than the supply of less carbon intensive fuels. However, the overall supply of carbon and especially the coal supply are much more price inelastic in Beckman et al. (2011).

6.1 Supply Elasticity of Carbon

How sensitive is the size of carbon leakage to the supply elasticity of carbon? To answer this question, the Annex I unilateral emissions abatement is simulated using two sets of value-added elasticities in coal, oil, and gas production, reported in table 3. Table 4 and Figure 9 show marginal costs of achieving Annex I emission reductions under different parametric assumptions. The alternative elasticity of carbon supply has relatively small impact on costs of achieving emission reduction targets. Figure 7 offers the comparison of the resulted leakage rates. Inelastic carbon supply results in very high leakage rate, rising to 35% in 2020. Burniaux and Troung (2002) parameters choice results in the much smaller leakage rate. This result is expected: if supply of fossil fuels would be perfectly inelastic, then it would be impossible to reduce their use and related emissions, and the leakage rate of any unilateral abatement would be equal to 100% (Burniaux, 2001).

6.2 Technological Flexibility

Technological flexibility is another important determinant for the size of the carbon leakage. Here we focus on the substitution among liquid fuels, between liquid and coal energy,

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[15] Krichene (2002) estimates the long-run supply elasticities for crude oil and gas over period from 1913 to 1999. Toman et al. (2008) do not conduct econometric estimation, but make assumptions about their elasticities of energy demand and supply. Their assumptions are intended to reflect long-term elasticities.

between electricity and fossil fuels, and then between energy and capital. Table 3 offers the comparison of the capital-energy and the inter-fuel substitution (last 4 lines in this table) employed in Burniaux and Troung (2002) and Beckman et al. (2011). The degree of technological flexibility in Beckman et al. (2011) is much smaller than is suggested by the standard GTAP-E set (see discussion about differences in time horizon above).

Figure 9 and Table 4 demonstrate that Annex I costs of achieving abatement targets are much higher under assumption of low degree of technological flexibility. Comparison of the carbon leakage rates obtained under the two specifications of technological flexibility (Figure 8) shows that the leakage is very sensitive to the assumption about the substitution elasticities and much higher at a low degree of technological flexibility. In Annex I, less flexibility results in larger reduction in the output to achieve the same emission cuts. This lost production is then picked up by non-Annex I countries leading to larger leakage. Recall that the supply of carbon is parameterized so that the supply of coal is much more price elastic than the supply of less carbon intensive fuels, leading to the reduction in international oil and gas prices relative to coal. Non-Annex I producers would shift to relatively cheaper low carbon fuels. This, however, becomes more difficult with rigid technological structure, leading to larger leakage. Burniuax (2001) provide useful discussion about the U-shaped relationship between carbon leakage and the degree of technological flexibility. This U-shaped relationship is driven by the relative strength of the demand and substitution effects. The demand effect refers to the reduction in Annex I demand for fossil fuels under the imposed emission cuts. The substitution effect refers to the inter fuel and fuel-factor substitution and depends on the degree of technological flexibility. When the degree of technological flexibility is small, the demand effect dominates – the demand for all fossil fuels declines in Annex I, international prices of oil and gas fall relatively more than the price of coal. Despite the change in relative prices, non-Annex I cannot shift to cheaper, less carbon intensive fuels, and resulted emission leakage is large.

The degree of technological flexibility is also an important determinant of the size of international capital reallocation channel of carbon leakage. If substitution possibilities between energy and capital are relatively low, as assumed in Beckman et al. (2011) parameters set, then emissions reductions will result in a larger fall in rates of return to capital in Annex I, compared to the case when producers have more flexibility and can substitute from energy toward capital. This loss of profitability will result in a larger outflow of capital from abating countries to countries that do not undertake emissions cuts.

7. Summary

This paper documents a dynamic CGE model GDyn-E that incorporates energy substitution, emissions from fossil fuel combustion and emission trading, and disequilibrium approach to international capital mobility. The paper provides illustrative experiment with the model, where Annex I countries unilaterally reduce their GHG emissions. Following the analysis of Burniaux (2001), the resulted carbon leakage is decomposed into international energy prices, structural, and international capital reallocation channels. Over time, in the absence of carbon free energy resources in the model, the carbon leakage grows and the channel of international investment reallocation becomes more important. The sensitivity analysis of the leakage rate with respect to parameterization of the production structure reveals that assumptions about technological flexibility and elasticity of carbon supply are important determinants of the size of leakage. The leakage through international capital reallocation channel is expected to be larger at a higher degree of complementarity between capital and energy.

While current version of GDyn-E model is useful for analysis of climate mitigation policies where international exchange is important, it has several limitations which will be addressed in the next version of the model. First, the model includes only CO_2 emissions from fossil fuel combustion, but does not include terrestrial carbon fluxes and non-CO_2 emissions, most of which are originated in agriculture. Review of recent studies indicates that while land using sectors account for one third of anthropogenic emissions, if incorporated into a global climate policy, these sectors could contribute up to half of all mitigation in the near term, at modest carbon prices (Hertel, 2012). So, it is important to incorporate non-CO_2 emissions from both industrial and agricultural activities, as well as emissions from land use change in GDyn-E model.

Second, while many of the climate policies discussed today are sector specific, investment and capital stock in current version of GDyn-E are defined at regional level only. To facilitate the analysis of the sector specific policies with GDyn-E, the data and the model should be modified to incorporate sector specific investment and sector specific capital stock accumulation.

Finally, it is important to mention that electricity sector is the largest single GHG emitter globally. Yet, its representation is very simple in both GTAP-E and GDyn-E. Disaggregation of this sector by type of electricity produced, including clean energy sources (wind, solar, hydropower, nuclear power), as well as introduction of bioenergy, will improve usefulness of the model for climate policy analysis.

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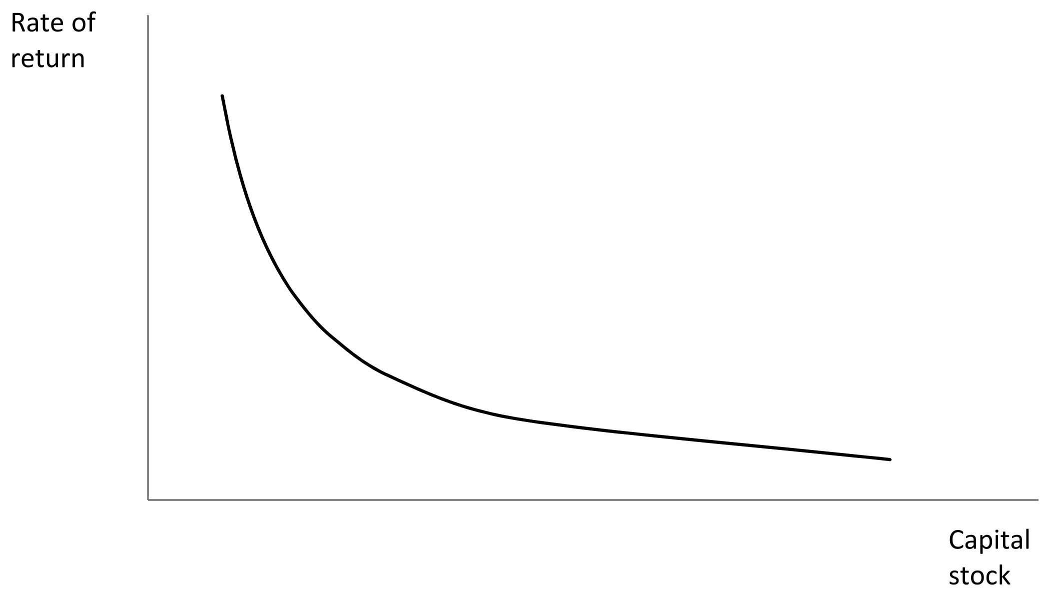

Figure 1. Downward sloping relationship between the rate of return and the capital stock

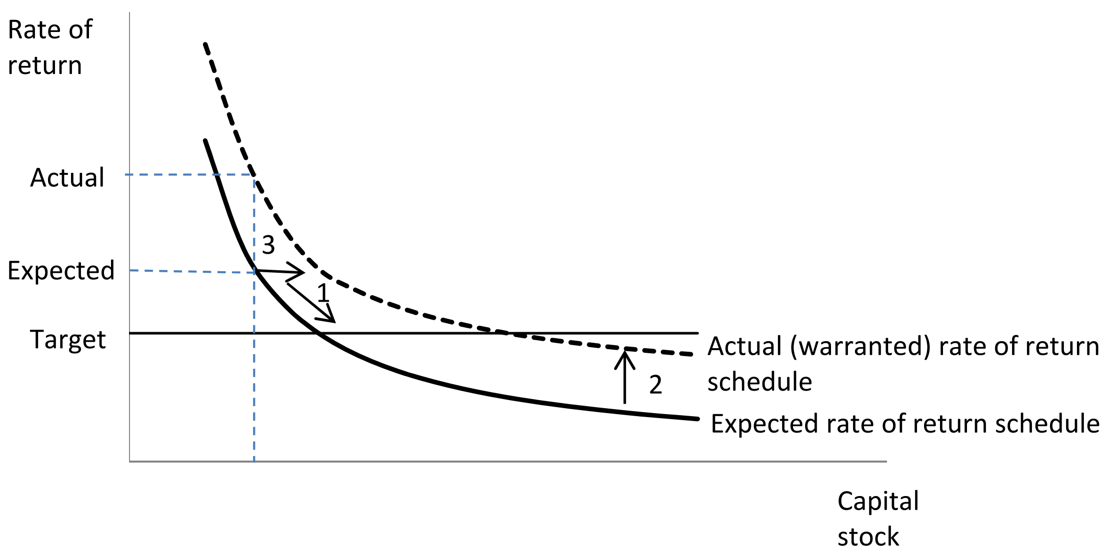

Figure 2. Three lagged adjustment mechanisms

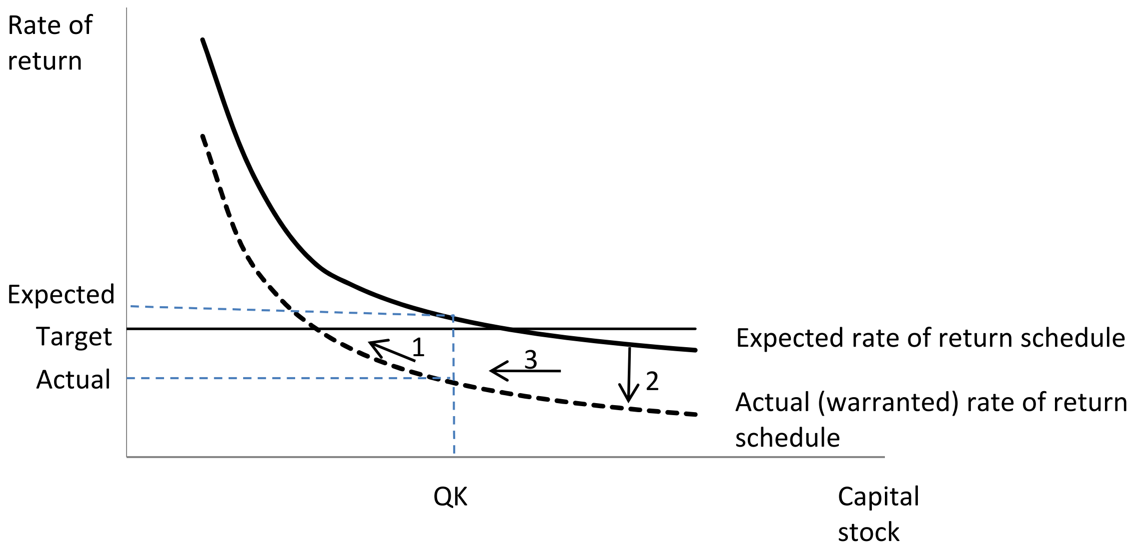

Figure 3. Impacts of Annex I emission reduction on Annex I rates of return

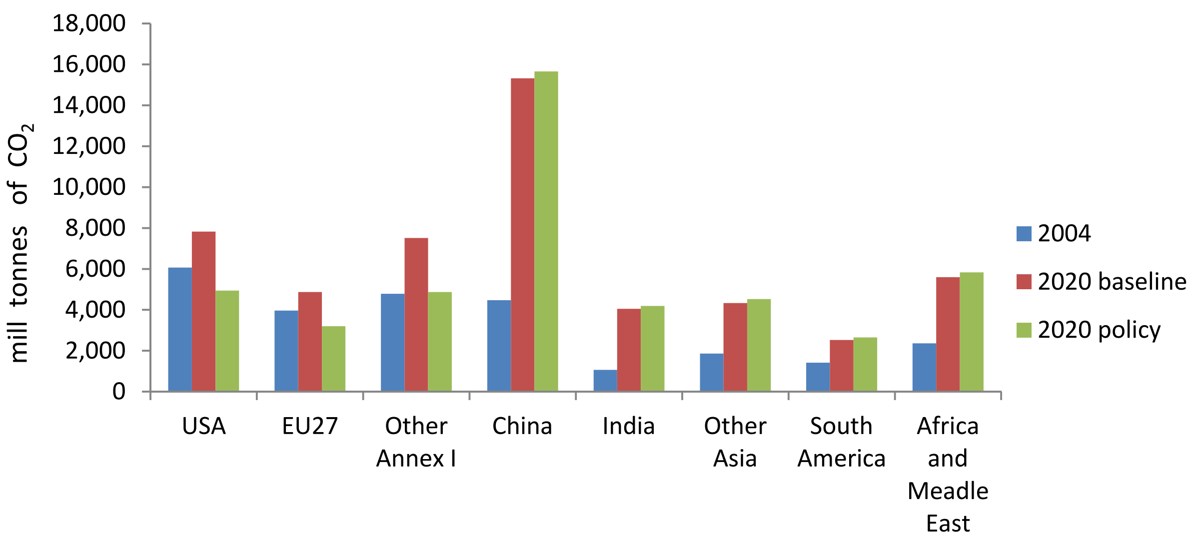

Figure 4. Combustion based CO_2 emissions in base year of the analysis and end of projection in baseline and illustrative scenarios.

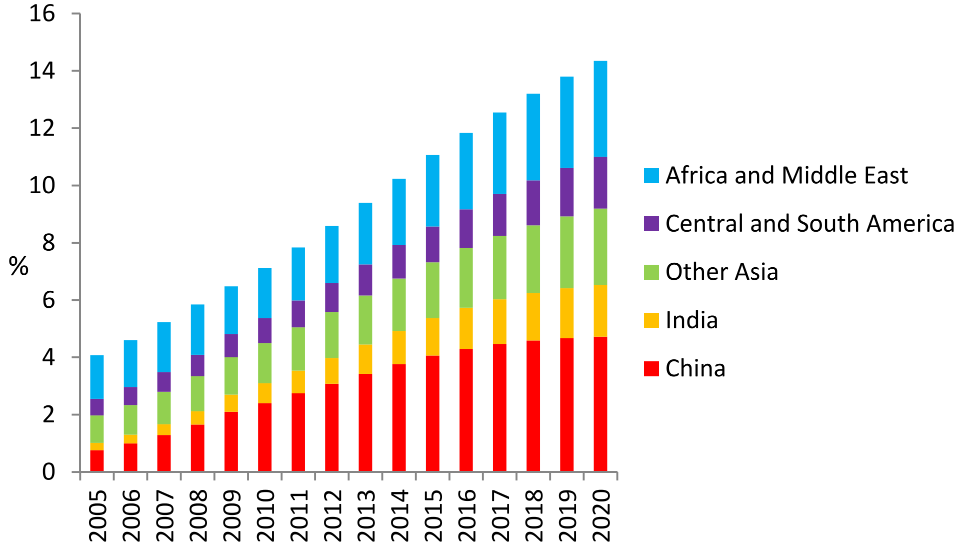

Figure 5a. Non-Annex I regions contribution to carbon leakage, %

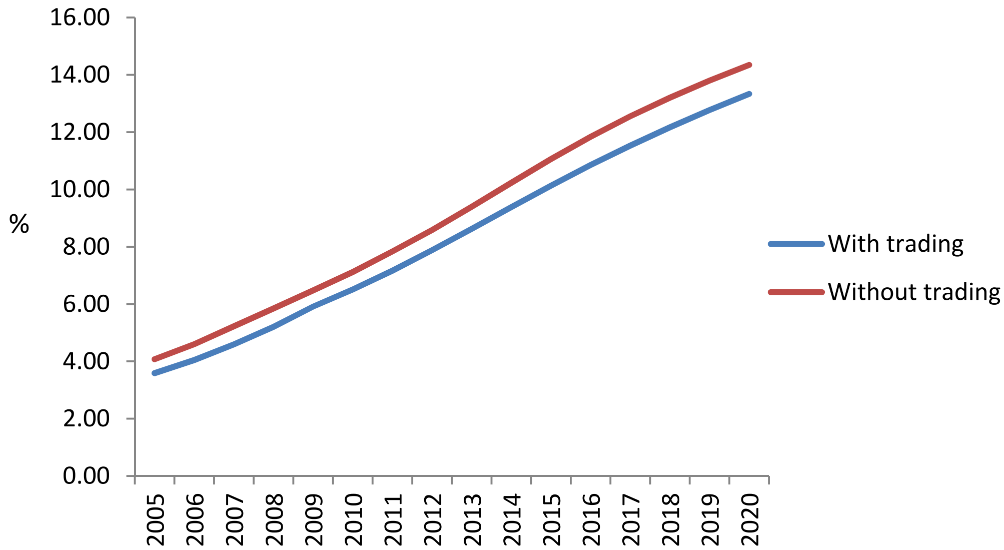

Figure 5b. Carbon leakage due to unilateral Annex I abatement, with and without emission permits trading, %

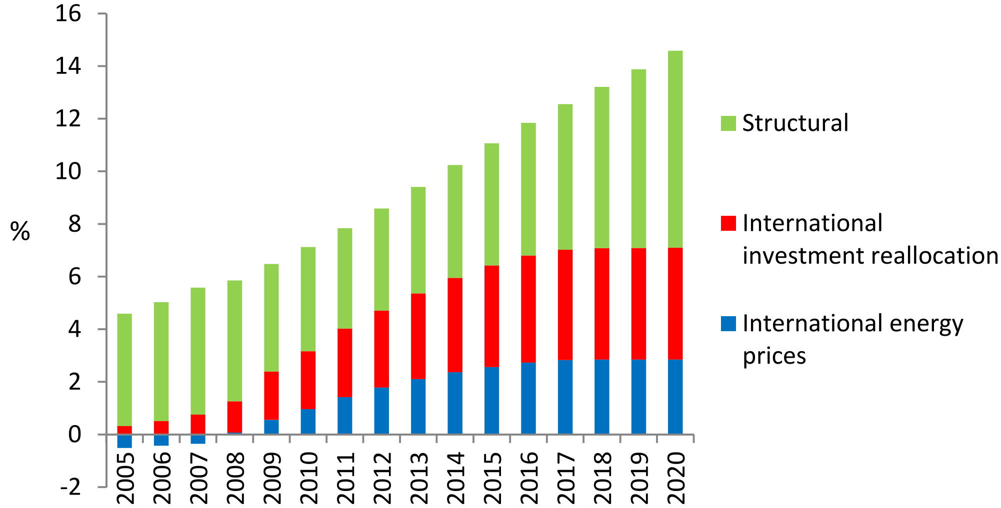

Figure 6. Decomposition of the carbon leakage into three channels: structural, international investment reallocation and international energy prices.

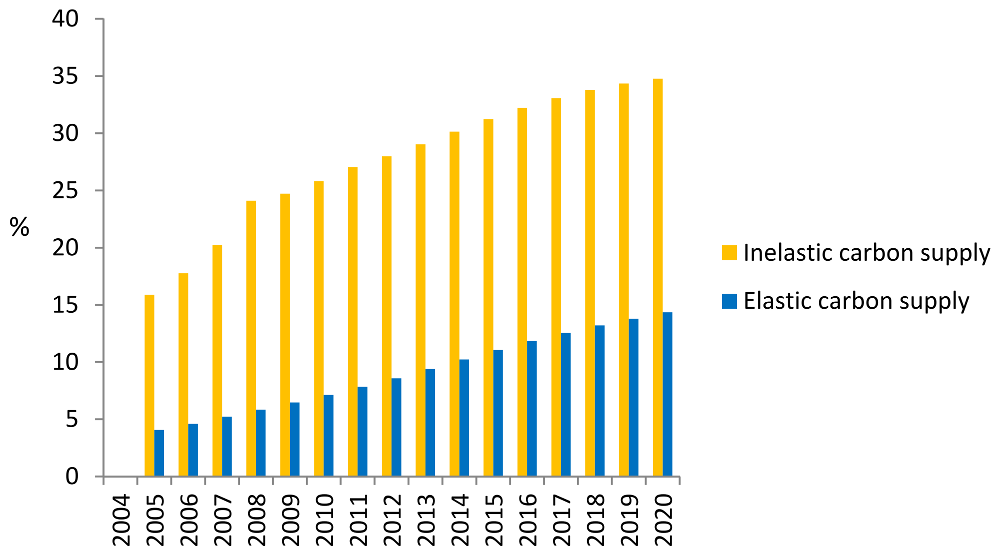

Figure 7. Carbon leakage due to Annex I unilateral GHG abatement under different assumptions about supply elasticity of carbon

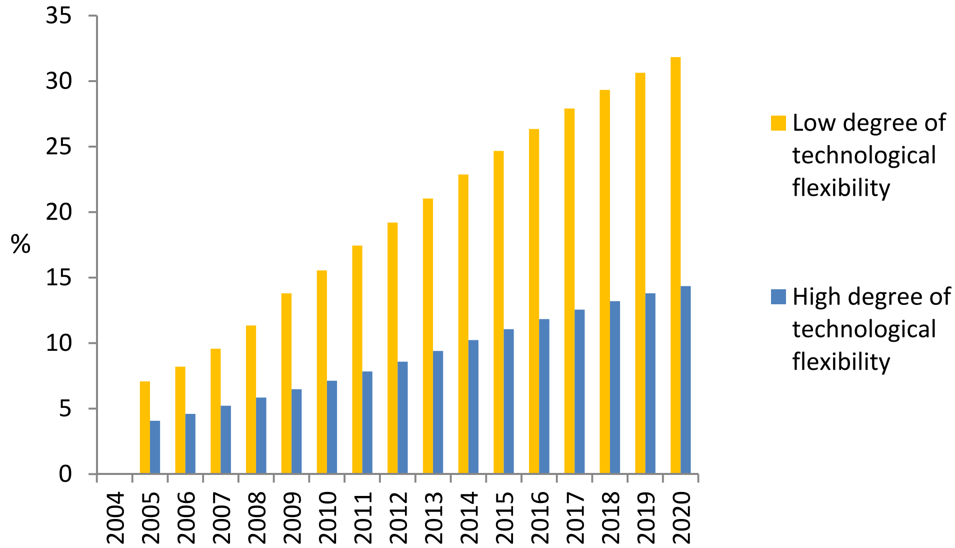

Figure 8. Carbon leakage due to Annex I unilateral GHG abatement under different assumptions about the degree of technological flexibility

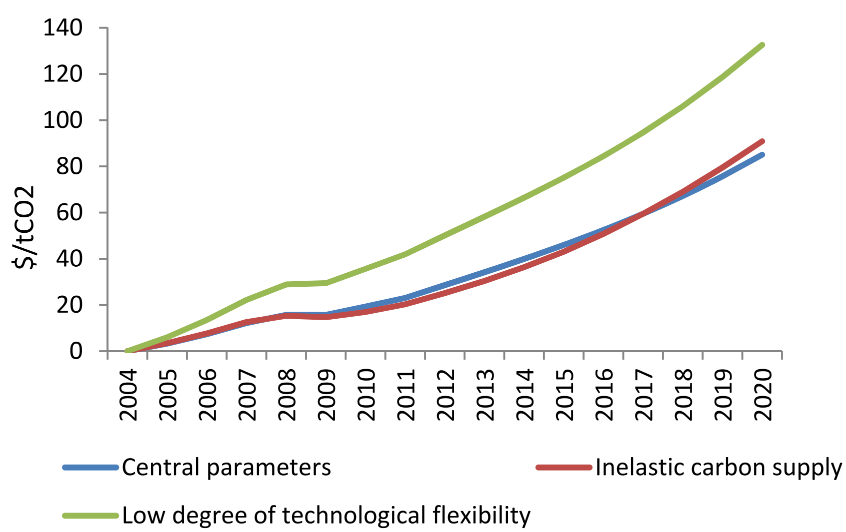

Figure 9. Annex I carbon tax in abatement scenario with central and alternative parameters. In each period, the carbon tax is calculated as a sum of abatement share weighted carbon taxes in Annex I regions.

Table 1. **Annual non-accumulable endowment productivity growth rate, and 2004-2020 cumulative growth rates in population, endowments and GDP, by region (%)**

Region	Population	Productivity (growth rate per year)	Unskilled labor	Skilled labor	Capital	GDP
1	2	3	4	5	6	7
USA	16	1.8	7	29	48.7	39
EU27	4	1.3	-11	34	44	28
BRAZIL	14	2.5	18	67	130	104
CANADA	16	1.8	13	32	66	45
JAPAN	-3	1.5	-21	26	18	14
CHIHKG	10	6.0	5	72	411	266
INDIA	23	5.0	29	98	441	248
C_C_Amer	19	3.0	24	92	30	63
S_o_Amer	19	2.0	22	83	255	115
E_Asia	7	2.0	0	61	276	110
Mala_Indo	18	3.5	21	100	290	159
R_SE_Asia	21	2.7	16	89	121	118
R_S_Asia	30	3.0	41	129	247	140
Russia	-6	3.0	-13	23	457	87
Oth_CEE_CIS	2	2.0	-2	41	179	95
Oth_Europe	10	1.3	-4	31	61	39
MEAS_NAfr	29	2.7	17	105	269	138
S_S_AFR	44	2.5	52	136	208	153
Oceania	22	1.4	22	40	86	59
South_Korea	5	2.0	-3	64	164	89

Source: Population and labor form Chappuis et al. 2011; capital and GDP from author's simulation.

Note: In China, annual productivity growth rate is assumed 6% over 2012-2015 and 5% over 2016-2020. In India, annual productivity growth rate is assumed 5% over 2012-2015 and 4% over 2016-2020.

Table 2. Annex I commitments to reduce emissions by 2020

Annex I region	Copenhagen commitment to reduce emissions by 2020	GDyn-E imposed change in emissions, %/year
EU27	20% compared with 1990	-1.158
Japan	25% compared with 1990	-2.6
Canada	17 % compared with 2005	-1.158
Oceania	New Zealand: 10-20% compared with 1990 Australia: 5-25% compared with 2000	-1.8
Russia	15–25 % compared with 1990	0.5
Other Europe	Norway: 30% compared with 1990	-3.6
Other CEE CIS	Belarus: 5–10 % compared with 1990 Ukraine: 20% compared with 1990	3.6
USA	17% compared with 2005	-1.158

Table 3. Production structure parameters

Element of GDyn-E production structure	Standard parameters (Burniaux and Troung)	Alternative parameters (Beckman, Hertel and Tyner)
Value added – energy in: Coal Oil Gas	 3 - 4 (supply el. 10) 0.32-0.4 (supply el. 1) 0. -1.55 (supply el. 4)	 0.32-0.4 (supply el. 1) 0.08-0.1(supply el. 0.25) 0. - 0.23 (supply el. 0.6)
Capital – energy (all)	0.5	0.25
Electricity – non electricity (all)	1	0.16
Coal – non coal (all)	0.5	0.07
Oil, gas, petroleum products (all)	1	0.25

Table 4. Impact of Annex I abatement on emissions and marginal costs of achieving the emission reduction targets

	Central parameters		Inelastic carbon supply		Low degree of technological flexibility	
	Change in emissions, %	Carbon tax in 2020, USD/tCO_2	Change in emissions, %	Carbon tax in 2020, USD/tCO_2	Change in emissions, %	Carbon tax in 2020, USD/tCO_2
1	2	3	4	5	6	7
USA	-37	65	-31	68	-35	98
EU27	-34	92	-28	94	-32	154
Other Annex I	-35	102	-23	124	-37	153
China	2	0	3	0	6	0
India	3	0	5	0	8	0
Other Asia	4	0	10	0	8	0
South America	5	0	12	0	9	0
Africa and Middle East	4	0	12	0	8	0
Global	-12		-7		-9	

Note: Changes in emissions are cumulative percentage changes deviations from baseline.

Appendix A

Regional propensity to save has two components, region specific *sdpsavereg*(*r*) and region generic *sdpsaveworld*.

Equation SDI
region specific determination of distribution parameter
(**all**,r,REG)
dpsave(*r*) = *sdpsavereg*(*r*) + *sdpsaveworld*;

This new equation and two variables introduced in GDyn-E are handy for implementation of the investment leakage decomposition to isolate the investment channel of carbon leakage. More specifically, the decomposition requires fixing investment in the policy run relative to baseline. This can be done vi risk premium or errors in expectations mechanism. In the illustrative application included with this paper, errors in expectations mechanism is chosen to fix investment in all but one region. In this remaining region, investment is fixed by endogenizing global shift in saving distribution parameter *sdpsaveworld.*

With standard GDyn treatment of savings, both components of *dpsave,* region-specific and region-generic are exogenous variables. If they are not shocked, then saving distribution parameter *dpsave* is zero as well, and propensity to save is (almost) fixed. In the alternative household saving behavior developed by Golub and McDougall (2012), the propensity to save is not fixed and is function of wealth to income ratio. It is determined by equation EXPRGWYR included below (for derivation and related variable-equation correspondence a reader is referred to Golub and McDougall, 2012). In GDyn-E model, a new slack variable *dpsaveslack* is added to the equation. This variable is endogenous and propensity to save is exogenous under the standard GDyn-E closure resulting in saving being in (almost) fixed proportion to income. To implement the alternative household saving behavior in the model, user will need to swap *dpsaveslack*(r) with variable representing changes in regional propensity to save *sdpsavereg*(*r*). Thus, *dpsaveslack* is exogenous under the alternative household saving behavior specification, and *sdpsavereg*(*r*) is endogenous.

Equation EXPRGWYR(**all**,r,REG)
erg_wyr(*r*)
= *SAVE*(*r*)/*WQHHLD*(*r*)*(*psave*(*r*)+*qsave*(*r*)-*wqh*(*r*))-*DYHAT*(*r*) + *dpsaveslack*(*r*);

Appendix B

There are several differences between GTAP-E version described in RM 15 and current GDyn-E technical implementation.

1. In GTAP-E model, a levels variable *VCTAX* represents carbon tax revenue by region from all sources and enters regional income equation. This treatment is revised in GDyn-E. Carbon tax revenue is combined with net permit trading revenue. Net permit revenue is defined as a product of nominal carbon tax rate and difference between emission quota and regional emissions:

   NCTAXLEV(*r*)*(*CO2Q*(*r*) – *CO2T*(*r*)).

If the difference is positive, then the region sells permits and its net permit revenue is positive. If the difference is negative, then the region buys permits and its net permit revenue is negative. The carbon tax revenue is defined as product of nominal carbon tax rate and regional emissions: *NCTAXLEV*(*r*)**CO2T*(*r*). Both net permit revenue and carbon tax revenue enter regional income equation. Sum of the two revenues is just *NCTAXLEV*(*r*)**CO2Q*(*r*), which enters regional income equation in difference form:

$$
\begin{aligned}
&INCOME(r) * y(r) \\
&= FY(r) * fincome(r) \\
&+ 100.0 * INCOME(r) * del\_indtaxr(r) \\
&+ INDTAX(r) * y(r) \\
&+ CO2Q(r) * NCTAXLEV(r) * gco2q(r) \\
&+ 100.0 * CO2Q(r) * NCTAXB(REGTOBLOC(r)) \\
&+ INCOME(r) * incomeslack(r);
\end{aligned}
$$

2. New carbon tax variables are introduced: change in ratio of non-carbon taxes to income, *del_tnctaxr*, and change in ratio of carbon tax to income, *del_ctaxr*.

3. The variable *DTBALCTRA* represents balance on current account, including the balance of trade and net emission trading revenue:

   $$DTBALCTRA(r) = DTBAL(r) + DVCO2TRA(r)$$

   In standard GTAP model, in order to maintain homogeneity in the presence of a fixed trade balance, we define a nominal variable *DTBALR* representing a trade balance to regional income ratio. Similar, to maintain homogeneity in the presence of a fixed current account, we define a ratio *DBALCAR*, which can be exogenized without losing price homogeneity:

   $$100 * INCOME(r) * DBALCAR(r) = 100 * DTBALCTRA(r) - TBALCTRA(r) * y(r)$$

Appendix C

Table C1 Aggregation of GTAP regions

Code	Region in the model	GTAP regions	Group
USA	United States	United States	Annex I
EU27	European Union	Austria, Belgium, Denmark, Finland, France, Germany, United Kingdom, Greece, Ireland, Italy, Luxemburg, Netherlands, Portugal, Spain, Sweden, Cyprus, Czech Republic, Hungary, Malta, Poland, Romania, Slovakia, Slovenia, Estonia, Latvia, Lithuania, Bulgaria	Annex I
BRAZIL	Brazil	Brazil	non Annex I
CAN	Canada	Canada	Annex I
JAPAN	Japan	Japan	Annex I
CHIHKG	China and Hong Kong	China, Hong Kong	non Annex I
INDIA	India	India	non Annex I
C_C_Amer	Central and Caribbean Americas	Mexico, Costa Rica, Guatemala, Nicaragua, Panama, Rest of Central America, Caribbean, Rest of North America	non Annex I
S_o_Amer	South and Other Americas	Argentina, Bolivia, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay, Venezuela, Rest of South America	non Annex I
E_Asia	East Asia	Taiwan, Rest of East Asia	non Annex I
Mala_Indo	Malaysia and Indonesia	Malaysia, Indonesia	non Annex I
R_SE_Asia	Rest of South East Asia	Combodia, Lao People's Democratic Republic, Myanmar, Philippines, Singapore, Thailand, Viet Nam, Rest of Southeast Asia	non Annex I
R_S_Asia	Rest of South Asia	Bangladesh, Pakistan, Sri Lanka, Rest of South Asia	non Annex I
Russia	Russia	Russian Federation	Annex I
Oth_CEE_CIS	Other East Europe and Rest of former Soviet Union	Ukraine, Rest of Eastern Europe, Rest of Europe, Kazakhstan, Kyrgyztan, Rest of Former Soviet Union, Armenia, Azerbaijan, Georgia, Turkey	Annex I
Oth_Europe	Rest of European Countries	Switzerland, Norway, Rest of EFTA	Annex I
MEAS_NAfr	Middle Eastern and North Africa	Iran, Rest of Western Asia, Egypt, Morocco, Tunisia, Rest of North Africa	non Annex I
S_S_AFR	Sub Saharan Africa	Nigeria, Senegal, Rest of West. Africa, Central Africa, South Central Africa, Ethiopia, Madagascar, Malawi, Mauritius, Mozambique, Tanzania, Uganda, Botswana, South Africa, Rest of South African Customs Union	non Annex I
Oceania	Oceania countries	Australia, New Zealand, Rest of Oceania	Annex I
South Korea	South Korea	South Korea	non Annex I

Table C2 Aggregation of GTAP sectors

Code	Sector in the model	GTAP commodities
Crops	All crops	pdr, wht, gro, v_f, osd, c_b, pfb, ocr
Ruminant	Ruminant meat and dairy	ctl, rmk, wol
Nonruminant	Non-ruminant livestock	oap
Forestry	Forestry	frs
OthPrimSect	Other sectors using natural resourses	fsh, omn
Coal	Coal: mining and agglomeration of hard coal, lignite and peat	coa
Oil	Oil extraction	oil
Gas	Gas: extraction; gas distribution: distribution of gaseous fuels through mains; steam and hot water supply	gas, gdt
Proc_rum	Processed ruminant meat products and processed dairy	cmt, mil
Proc_nonrum	Processed non-ruminant meat products	omt
PrFood	Processed food	vol, pcr, sgr, ofd, b_t
Oil_Pcts	Petroleum, coal products	p_c
En_Int_Ind	Energy intensive Industries	crp, i_s, nfm
Electricity	Electricity	ely
Cement	Non-Metallic Minerals: cement, plaster, lime, gravel, concrete	nmm
Water	Water: collection, purification and distribution	wtr
Other_transp	Other transport	otp
Water_transp	Water transport	wtp
Air_transp	Air transport	atp
Oth_Ind_Se	Other industry and services	tex, wap, lea, lum, ppp, fmp, mvh, otn, ele, ome, omf, cns, trd, cmn, ofi, isr, obs, ros
NTrdServices	Public Administration, Defense, Education, Health, Dwellings	osg, dwe

Appendix D

Several experiments are included in the model application accompanying this paper.

1. Annex I abatement.zip is baseline and Annex I emission reduction without emission trading among Annex I.
2. Annex I abatement with trading.zip is baseline and Annex I emission reduction with emission trading among Annex I. Note, separate baseline simulation is required due to scenario specific sets file that defines Annex I bloc.
3. Decomposition 1.zip contains simulation details of the baseline and the first intermediate scenario used to decompose total carbon leakage. This intermediate scenario has the same features as the policy scenario (Annex I emission reduction), except that the prices of the primary fossil fuels (coal, crude oil, and natural gas) are kept constant at the same level as in the baseline scenario.
4. Decomposition 2.zip contains simulation details of the baseline and the second intermediate scenario used to decompose total carbon leakage. This intermediate scenario assumes that both the prices of the primary fossil fuels and the capital stock in each region are kept fixed at the same level as in the baseline scenario.

   Alternative parameters file gpar_EVFE.har is the same as gpar.har except it contains alternative elasticity of substitution in value added (parameter ELFVAEN) calibrated to mimic fossil fuels supply response based on the literature review reported in Beckman et al. (2011). Another alternative parameter file is gpar_FLEX.har containing alternative substitution elasticities between capital and energy (ELFKEN), electricity and other energy composite (ELFENY), within non-electrical energy composite (ELFNELY), and among non-coal fossil fuels (ELFNCOAL). The choice of these parameters is described in Beckman et al. (2011).

In policy scenario, Annex I regions gradually reduce emissions from 2004 to 2020 relative to emissions in a base year. Annex I regional emission reduction targets converted to equal annual shocks (Table 2). These shocks should be applied from 2004 to 2020 in the policy run. However, in year 2009, shocks and closure are different from shocks and closure used in other years of the policy run – exogenous emissions reductions were imposed only in Oceania and "Other Europe" (Oth_Europe). The reason for this is that 2009 is a recession year reflected in GDP projections. Because of the recession, baseline emissions fall in all Annex I regions, except Oceania. Among those Annex I regions where emissions fall in 2009, only Oth_Europe baseline emission reductions are larger than those suggested by the policy experiment. Thus, imposition of the emission reductions in 2009 in these (other than Oceania and Oth_Europe) Annex I regions would result in negative carbon tax (carbon subsidy). This situation is avoided by not imposing emission reduction targets in 2009 in all Annex I regions, except Oceania where baseline emission are rising in recession year, and Oth_Europe where emission reduction in baseline is still smaller than the policy reduction.