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The Kyoto Protocol: 'Hot Air' for Russia?

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Abstract

The Kyoto Protocol sets the carbon emission targets for 2008-2012 for the major emitting countries. Several former Soviet countries have emissions quotas that appear to be in excess of their anticipated emissions as a result of economic downturn. This excess is sometimes referred to as "hot air", and could, in principle, be traded with other countries. The "hot air" estimates range from 150 to 500 MtC, while the other signatory countries are projected to reduce their emissions by a total of 800-900 MtC. For political reasons, only Russia and Ukraine, who together account for approximately two-thirds of the total size of the "hot air", are likely to sell it. The signatory countries are divided into two polar groups based on their views toward the principles of international emission trading. One group proposes a ceiling on the amount of traded emission permits because of a stated preference for higher domestic abatement activities. The other group advocates unrestricted trade because of its efficiency. Based on a global computable general equilibrium model, the ceiling proposal implies substantial welfare losses while failing to reduce total emissions significantly. Welfare estimates for Russia vary enormously depending on the proposed principles of emission trading. However, Russia alone cannot impose a credible threat of removing itself from the Kyoto agreement if the ceiling were imposed. An alliance with the other signatory countries who experience high mitigation costs and who want to exploit the full efficiency of free trade in carbon permits makes adoption of the ceiling proposal questionable.

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1 Introduction

There is a wide consensus among the scientists that increased emissions of "greenhouse gases" (where carbon dioxide, CO_2, is the major component) resulting from economic and demographic growth will cause significant global warming by the middle of the 21-st century in the absence of policy intervention (see, for example, Bruce *et al* (1996) for a review). The international response to climate change is a negotiating process embodied in the United Nations Framework Convention on Climate Change (UNFCCC, 1992) and its Kyoto Protocol (UNFCCC, 1997).

The Kyoto Protocol calls for industrialized countries and economies in transition to limit their emissions by the first part of the 21-st century. The countries are listed in the protocol in Annex B, so they are called Annex B countries[1]. On average, these countries have committed themselves to reduce carbon emissions by 4% from 1990 levels in the period 2008-2012, or 12% below the commitment period projections (DOE, 2000). The protocol allows creation of different systems for emission reduction trading. Most countries expect to have higher emissions in the commitment period than in 1990. However, as a result of decline in economic activity, carbon emissions in the transitional economies of Eastern Europe (EE) and the former Soviet Union (FSU) decreased by 34% between 1990 and 1997. Despite the economic recovery, economies in transition have projected 2010 carbon emissions lower than in 1990. These countries can sell their excess emission permits to other Annex B parties. The situation in which a party can sell emission permits virtually at no cost to itself is sometimes referred to as "hot air"[2].

This paper explores the rules of carbon emission trading and the economic effects of the European Union proposal (UNFCCC, 1999) on the countries of the former Soviet Union, notably Russia. The main contribution of the paper is the quantitative assessment of Russia's different strategies in regard to the proposed ceilings on the amount of traded emissions. Without implementing unrestricted trade, Russia and Ukraine have an incentive not to ratify the Kyoto Protocol. However, they alone cannot impose a credible threat of removing themselves from the Kyoto agreement if the ceiling were imposed. An alliance with the other signatory countries who experience high mitigation costs and who want to exploit the full efficiency of free trade in carbon permits would make adoption of the ceiling proposal questionable. Indeed, with the possibility of exchanging excess carbon emissions, all countries would find it more economically attractive to ratify the protocol.

One of the first estimates of the number and value of permits that were granted to Russia and Ukraine is done by Victor *et al* (1998), where this phenomenon is termed as "carbon bubble"[3]. In their reference case, the total size of the annual "bubble" is 344 millions of metric tons of carbon (MtC), where Russia and Ukraine account for 225 MtC, which is worth $4-34 billion. This flow of assets is comparable with Russian earnings from natural gas exports. The study points out that only Russia and Ukraine are likely to sell "bubble permits" because it may be politically difficult for the other economies in transition to do so due to their desire to develop close economic ties with the EU. Indeed, later on Eastern European associates of the EU co-signed the EU proposal (UNFCCC, 1999) to impose a "cap" on the emission trading.

Numerous models have been created to estimate the future level of carbon emissions (Morita, 1998; Weyant, 1999; DOE, 2000). For example, the recent *International Energy Outlook (IEO)* (DOE, 2000) reports that annual energy-related carbon emissions are projected to rise from ap-

[1]For a full list of the Annex B countries, see Appendix 1.

[2]Our research has not discovered any clear authorship of the term "hot air". Before the Kyoto agreement the term referred to the situation when sinks (such as forests or soils which can absorb carbon dioxide from the atmosphere) could be credited against emission reductions. The European Union position on emission trading during the 1998 meeting of the Subsidiary Bodies of the UNFCCC defines "hot air" as the situation when assigned amounts of emissions are higher than the expected emissions in the commitment period (UNFCCC, 1998). The current UNFCCC online glossary describes "hot air " as the concern that some governments will be able to meet their commitment targets with minimal effort and could then flood the market for emissions credits, reducing the incentive for other countries to cut their own domestic emissions.

[3]Victor *et al* (1998) states that observers politically hostile to the Kyoto allocation of carbon permits for the former Soviet Union have termed the situation as "hot air". In our analysis we use both terms, "hot air" and "carbon bubble", interchangeably without assigning any value judgement to them.

proximately 5840 MtC in 1990 to 8150 MtC in 2010 (with the Annex B share being 4255 MtC) in the absence of carbon reduction efforts. Under the terms of the Kyoto Protocol, the Annex B industrialized countries are expected to cut their emissions by 836 MtC, while 318 MtC are projected to be available from all EE and FSU countries for possible trading. The models differ in their projections but many of them show that meeting the Kyoto targets implies a drastic reduction in carbon emissions for some countries, such as the USA, Canada, and Japan, which are required to cut about 25-35% of their 2010 emissions. Marginal abatement costs are different among the countries. The costs depend on the required cutback, carbon intensity and substitution possibilities in different sectors across countries. The models are almost uniform in their estimates that Japan has the highest mitigation costs despite the wide differences in the projections for the other countries.

There is a disagreement between the Annex B countries on the rules for emission permit trading. The European Union is opposed to the sales of emission permits without supplemental domestic abatement activities because of a stated preference for higher domestic abatement activities. This position is strictly rejected by the USA and other countries which advocate efficiency gains from unrestricted international trading of carbon permits. Indeed, due to the fact that the Annex B countries have different marginal abatement costs (Weyant, 1999, EMF, 2000), the Kyoto targets without emission trading would lead to misallocation of resources and distortions in international competition.

Different views on carbon emission trading are based on perceived costs of meeting the Kyoto obligations. The UMBRELLA group[4], which are required to cut 14% of their projected 2995 MtC in 2010 (DOE, 2000), are pessimistic about the possibility of meeting their commitments through purely domestic efforts. Emission trading lowers the cost of meeting reduction targets by exploiting differences in marginal abatement costs across countries.

The EU and associates[5], with 8% projected reduction of 1260 MtC, are optimistic regarding domestic abatement costs and do not feel the same need for carbon trading except as a tool for relaxing conjectural tensions (Hourcade, 2000). The EU stresses that any trading should be "supplemental" to domestic actions. Their goal is to limit possibilities of "buying out" of the obligations for importers of "hot air" and to restrict the countries who gain from the emission trade without reducing domestic emissions.

It should be noted that US emissions account for approximately 60% of the UMBRELLA group, 40% of the total Annex B emissions, or 20% of the world emissions. Carbon emissions in the European Union and associates account for 30% of the total Annex B emissions, or 15% of the world emissions. The absence of a ratification of the Kyoto Protocol by the USA would leave the major player out of the game. An additional concern of the UMBRELLA group is that restrictions on emission trading will undermine credibility of the Kyoto goals and future negotiation process. The possibility of banking unused emission permits for use in the future periods, as it is stated in the Kyoto Protocol, makes restrictions questionable anyway.

The rest of the paper is organized in the following way. Section 2 discusses emission trading and the proposal submitted to UNFCCC by the European Union and its associates. Section 3 provides an overview of the data for actual and projected emissions of the former Soviet Union and Eastern Europe. Section 4 describes the structure of the model employed in this paper. Numerical results are discussed in Section 5. In section 6 we summarize and conclude.

2 Emission Trading

The Kyoto Protocol introduces three market mechanisms by which the Annex B countries can achieve part of their targets at a lower cost than at home: emission trading (Article 17), joint

[4] USA, Canada, Japan, Australia, New Zealand, Iceland, Norway, Russia, and Ukraine.

[5] EU associates include Bulgaria, Croatia, Czech Republic, Estonia, Latvia, Lithuania, Hungary, Poland, Slovakia, and Slovenia.

implementation (Article 6), and the clean development mechanism (Article 12). Emission trading assumes a trade of emission allowances with each other. The joint implementation (JI) is obtaining credits for emissions avoided by investment in projects in other Annex B countries. The clean development mechanism (CDM) is obtaining similar credits from projects in developing countries that also contribute to their sustainable development. The Protocol does not specify the exact rules for implementation of these mechanisms. We focus our attention on the issues of emission trading.

Economic reasoning predicts that international trade in carbon emission rights can reduce mitigation costs. Any restrictions reduce gains from trade. Costs are lowest when there is full global trading. That is, when reductions are made where it is least expensive to do so regardless of their geographical location. As confirmed by the modeling results presented in the 1999 special issue of the *Energy Journal* (Weyant, 1999), free trade significantly reduces the total cost of meeting reduction targets.

2.1 The European Proposal

Article 17 of the Kyoto protocol states that emission trading should be supplemental to domestic actions for the purpose of meeting quantified emission limitation and reduction commitments. However, supplementarity is not defined in the Protocol. In 1999, the European Union submitted a proposal (UNFCCC, 1999) for limits on the share of emissions reductions a country might obtain through use of emission trading. The proposal defines the rules for buyers and sellers in the following way:

"Net acquisitions by an Annex B Party for all three Kyoto mechanisms together must not exceed the higher of the following alternatives: 5% of (base year emissions multiplied by five plus assigned amount/2), or 50% of the difference between the actual emissions of any year between 1994 and 2002 multiplied by 5, and its assigned amount.

Net transfers by an Annex B Party for all three Kyoto mechanisms together must not exceed: 5% of (base year emissions multiplied by five plus assigned amount/2).

However, the ceiling on net acquisitions and on net transfers can be increased to the extent that an Annex B party achieves emission reductions larger that the relevant ceiling in the commitment period through domestic action undertaken after 1993, if demonstrated by the Party in a verifiable manner and subject to the expert review process to be developed under Article 8 of the Kyoto Protocol."

Different researchers have different interpretation of the provisions stated above. Baron *et al.* (1999) at the International Energy Agency reported an analysis of the implications of the proposal. Their interpretation is that the proposal does not put a restriction on the total amount of emission units that can be sold, as it only puts a restriction on the amount of emission units that can be sold by Annex B Parties. However, the Kyoto Protocol mentions the emission trading *among* the Annex B countries only. International agreement about emission permit trading of the non-Annex B countries, which do not have any reduction commitments, is unlikely to be achieved. It is our guess that Baron *et al* use global trading as a proxy for CDM, which is another important mechanism introduced in the protocol. The economic analysis of CDM is much more complicated than the analysis of emission trading because of the huge uncertainty related to the rules of implementation of CDM.

In the analysis by Baron *et al*, all economies in transition except Slovenia are assumed to be sellers of the emission permits and all other Annex B countries are assumed to be buyers. For buyers, the estimated potential gap between the Kyoto targets and 2010 emissions is 819.5 MtC. Under the EU proposal, these countries are able to buy only 297.5 MtC, while the amount that can be sold is restricted to 52 MtC. In general, excess demand leads to increase in price. However, Baron *et al* predict a possibility of a lower price for emission units based on their reading of the EU proposal (restricted demand and unrestricted non-"hot air" supply).

Jensen *et al* (2000) argue that the most important ceiling is the ceiling described in the "however" clause. They notice that an Annex B country can sell as many emission permits as they want provided that they can verify that a similar volume of domestic abatement has been undertaken after 1993. However, the verification procedure is not defined in the EU proposal. The introduction of such verification will be costly. It is possible to measure the level of emissions but it is problematic to quantify the level of domestic abatement activities that would have existed in the absence of the Kyoto agreement.

Jensen *et al* apply a dynamic computable general equilibrium model to analyse the economic effects of the EU proposal. Their interpretation is that the proposal bans the sale of "hot air" but otherwise an Annex B country is allowed to sell any volume of emission permits as long as domestic abatement ratio is not less than 50% of the abatement requirement ("Proposal B"). They contrast their interpretation with the situation where "hot air" is not excluded but the requirement of domestic abatement is maintained ("HotAir"). Jensen estimated a global welfare cost of the introduction of the European Proposal as 14 billion of 1995 $ for the "Proposal B" scenario and 12 billion for the "HotAir" scenario. In the short-run, the EU proposal drives up the price for carbon permits. In the long-run, the proposal drives down the price due to binding import ceilings. "Hot air" exporters lose from the proposal, but lose even more under the global emission trade. However, the authors did not mention that those huge loses would happen in the case of *restricted* global trading. The results of their modeling are obtained under the assumption that the proposal stays forever, there are no administrative costs for verification procedures, banking of unused emission permits is not allowed (which is a contradiction of Article 3.13 of the Kyoto Protocol), and there is a possibility of global carbon permit trade (which, again, is not in the Kyoto Protocol).

Bohringer (2000) proposed "cooling down" strategies to satisfy both the UMBRELLA group and the European Union. The strategy requires scaling down Kyoto targets to eliminate "hot air". He shows that all countries are better off using these strategies for emission trading than without any trading. However, it will be politically difficult to impose stricter emission cutback requirements.

2.2 Economics of the European Proposal

Different aspects of the economic consequences of demand and supply ceilings are analysed in Baron *et al* (1999) and Jensen *et al* (2000). The potential effects of the European proposal can be illustrated with the diagrams presented in Figures 1-3.

Figure 1.a shows demand and supply schedules for carbon permits, where the world market price is P_u in the unrestricted trade equilibrium. When demand is restricted, the demand schedule moves from abD_0 to abD_r. At the price P_u there is excess supply, and the price decreases to to P_r to clear the market. The restriction creates a dead weight loss (the black dotted triangle) being split between the buyer and seller and an income transfer from seller to buyer (the rectangle with empty circles inside) due to the lower price on all permits sold.

Figure 1.b shows the marginal abatement cost curve (MAC) for a net permit importer. The level of abatement increases and the level of emissions decreases along the X-axis. The origin corresponds to the business-as-usual case B with no abatement activities. The assigned amount of emissions is K. If a country is restricted to only domestic abatement activities, the MAC is equal to c. In the case of unrestricted trade, the country chooses to abate A_u units domestically and import permits up to K. When imports are restricted, permit imports must decrease and domestic abatement increases to A_r. The country experiences a welfare gain equal to the rectangular circled area due to the lower world market price on all imported permits, but also a welfare loss due to the extra costs of abating domestically equal to the black dotted triangle.

Figure 1.c shows that the permit exporter always loses, partly due to the lower price of permits and partly due to a lower volume of trade. The lower price of permits decreases domestic abatement from A_u to A_r as it is now less profitable to abate domestically and sell the released permits.

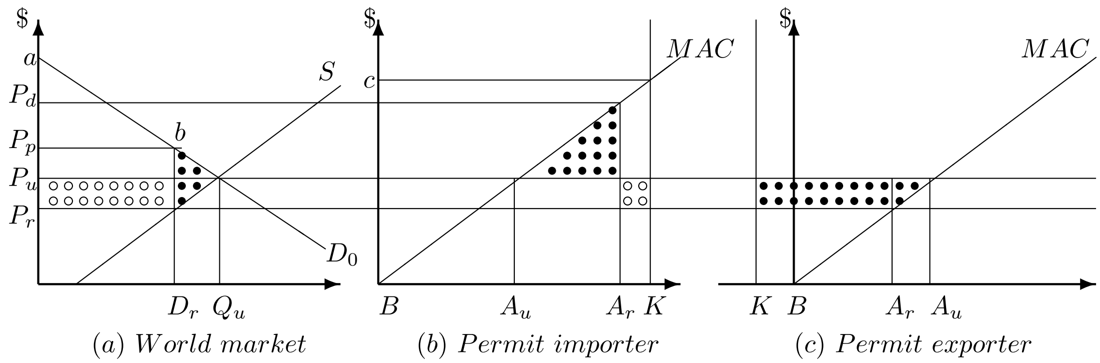

Fig. 1. A ceiling on demand.

Demand side restrictions have no impact on the sale of "hot air" unless total demand is reduced below the volume of available "hot air". It should be noted that if "hot air" is restricted, an exporting country has an opportunity to increase its emissions to an amount which would lie between K and B (which would correspond to negative abatement activities) on Figure 1.c.

Figure 2 shows the consequences of a binding ceiling on the supply side. All other things being equal, a binding ceiling creates excess demand, increasing the world market price from P_u to P_r to clear the market as seen in Figure 2.a. There is also a dead weight loss in this case, but now the income transfer goes from buyer to seller. Due to a higher price on permits, an importing country in Fig. 2.b. increases its domestic abatement from A_u to A_r. The importing country loses from the higher price on permits and from the higher costs of domestic abatement. Domestic abatement increases because of the higher opportunity costs of buying permits on the market.

The exporting country (Fig.2.c) has a gain when the income transfer from higher prices is bigger than the loss of revenue from the lower level of permits sold, and an economic loss when the opposite holds.

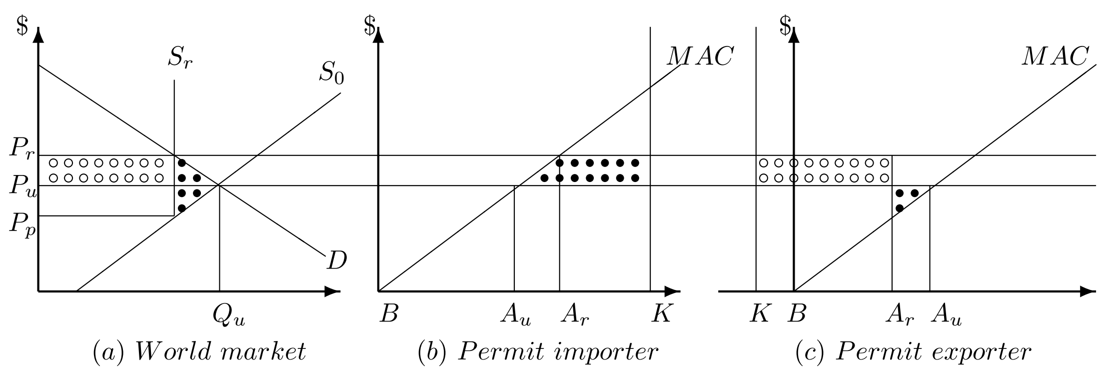

Fig. 2. A ceiling on supply.

As in the case of demand side restrictions, a ceiling on supply has no impact on the sale of "hot air" unless total supply is reduced below the volume of available "hot air". It is important to note that a ceiling on a quantity is equivalent to a quota, therefore, the resulting market price for permits will lie between P_p and P_r depending on quota rents allocation.

Jensen *et al* (2000) argue that on the supply side, the "however" clause of the EU proposal is not a ceiling but rather a deduction requirement. Figure 3 illustrates the effects of a supply side deduction. The exclusion of "hot air" from the market reduces the supply of permits from S_0 to S_d and drives up the market price from P_u to P_r.

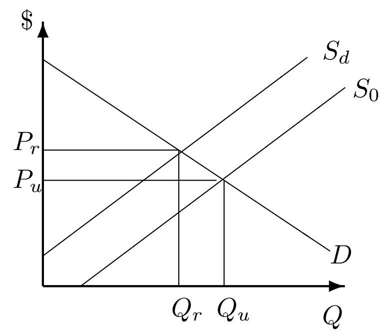

Fig. 3. Supply-side deduction.

In all three cases, the results would be different if either buyers or sellers were able to exploit their market power. If "hot air" is not eliminated from the market and Russia and Ukraine form a stable duopoly then the price of permits will be higher. The opposite effect can happen if the importers of permits are able to exercise a monopsony power.

3 Data

In order to analyse the economic effects of the Kyoto Protocol and the European Proposal we use a global economic-energy dataset GTAP-EG (Rutherford and Paltsev, 2000), where we have combined the GTAP economic data (Hertel, 1997) with the IEA energy data. The resulting dataset characterizes production and bilateral trade flows in 1995, including tax rates on imports and exports. For our analysis we calibrate the data to the year 2010 using different exogenous GDP projections (DOE, 1998; Victor, 1998).

It should be noted that different sources report different levels for 1990 former Soviet Union (FSU) emissions. Most of the publications provide the data for the FSU as a single region. In our opinion, the most reliable data come from the UNFCCC[6], the US Department of Energy International Energy Outlook (DOE, 2000), the OECD International Energy Agency (IEA, 1997), and the International Institute for Applied Systems Analysis[7] (Victor, 1998).

Table 1 reports the data for 1990 FSU emissions, associated Kyoto Protocol targets, projected 2010 emissions, the Kyoto-required cutback as a percentage of 2010 emissions, and the size of the "carbon bubble" in millions of metric tons of carbon (MtC). The International Energy Outlook reports extensive data for three different scenarios: low growth (IEOlow), reference growth (IEOref), and high growth (IEOhi). Note that Table 23 of the International Energy Outlook (IEO23) reports emissions for only those FSU countries included in Annex I of the 1992 Convention. Unfortunately, in many cases the publications do not specify the countries included in the FSU aggregate. Indeed, there are 15 countries of the former Soviet Union. Annex B of the Kyoto Protocol lists five of them: Russia, Ukraine, Latvia, Lithuania, and Estonia. In many references to "hot air", only Russia and Ukraine are mentioned as the FSU countries, while the Baltic states are recognized as the EU associates. In addition, Belarus is listed in the Convention's Annex I (UNFCCC, 1992), but not included in the Protocol's Annex B, as it was not a Party to the Convention when the Protocol was adopted.

[6]UNFCCC has an online database at http://www.unfccc.int
[7]IIASA has an online database at http://www.iiasa.ac.at/cgi-bin/ecs/book_dyn/bookcnt.py

	1990	Target	2010	Cutback(%)	Bubble
IEOlow	1034	1013	697	-45	316
IEOref	1034	1013	728	-39	285
IEOhi	1034	1013	797	-27	216
IEO23	854	853	591	-44	261
IIASA	1026	1005	748	-34	257

Table 1. Data for FSU carbon emissions (MtC).
Sources: DOE (2000), Victor et al (1998)

The Kyoto-related models have much wider discrepancy in terms of the 1990 data for the FSU region and 2010 projections. Some of the results (Morita, 1998) are presented in Table 2.

	1990	2010	Cutback(%)	Bubble
AMOCO	974	968-1110	-1.4 : +14.0	0-6
ICAM2/IMF14	1500	1500-1700	0 : +13.5	-
GREEN	1059	1739	+40.3	-
RICE	960	780-1257	-20.6 : +25.2	0-180
WorldScan	993	1122-1746	+13.3 : +44.3	-
YURI	965	910	-3.9	55
MIT/IMF14	960-1023	899-1728	-11.5 : +45.6	61
MERGE/IMF14	960	754-811	-24.8 : -16.0	149-206
AIM/SRES	1216	892-1150	-33.6 : -3.6	66-324

Table 2. Data for FSU carbon emissions (MtC) from different models.
Source: Morita (1998)

Table 3 shows the 1990 carbon emissions data for the potential “hot air” sellers, FSU and Eastern Europe, compiled from the different data sources. Note that Table 23 of the International Energy Outlook reports carbon emissions for Annex I FSU as being 854 MtC. Summation of UNFCCC statistics for Annex B FSU countries gives 867 MtC. Another Annex I FSU country (but not Annex B country) is Belarus, which accounts for 25-30 MtC according to different sources (but not reported by UNFCCC). It follows that even for 1990 emissions the data for the Annex I FSU region differs by approximately 40 MtC in two widely recognized publications.

Region	Data and Source
Russia	647 (UNFCCC)
Ukraine	192 (UNFCCC), 182 (IEA, IIASA)
Russia+Ukraine	839 (UNFCCC)
Baltics	27.8 (UNFCCC), 17.1 (IEA)
Annex I FSU	854 (DOE), 867 (UNFCCC)
Annex I EE	281 (DOE)
Annex I EE/FSU	1135 (DOE)
FSU	1034 (DOE), 1026 (IIASA)
EE	303 (DOE)
EE/FSU	1337 (DOE)

Table 3. 1990 carbon emissions by the potential “hot air” sellers (MtC)
Sources: UNFCCC (2000), DOE (2000), IIASA (1998), Baron (1999).

In our analysis we use FSU data as a proxy for Russian and Ukrainian economic and energy-related data because of the structure of the GTAP dataset, which does not report statistics of individual FSU countries. Table 4 presents Russia’s and “Russia plus Ukraine”’s shares as a percentage of emissions by the other potential exporters of the “hot air”. Russia and Ukraine account for approximately 80% of FSU emissions. The deviation is much bigger for the models which use the EE/FSU combined region for all economies in transition.

	R+U	Annex I FSU	Annex I EE/FSU	FSU	EE/FSU
Russia as a percentage of	77.1	75.8	57.0	62.6	48.4
Russia and Ukraine as a percentage of	100	98.2	74.0	81.1	62.7

Table 4. Calculated percentage of emissions by "hot air" sellers.

Russian national estimates of its "carbon bubble" are very different from the above mentioned databases. Table 5 reports Russian projections reported to UNFCCC in 1995, 1997, and 1999. The 1998 Russian crisis resulted in negative 5% GDP growth in 1999 and decrease in the level of projected emissions. Taking into account that Russia emits 75% of Annex I FSU carbon emissions, even the pessimistic scenario projects the size of its "carbon bubble" much lower than IEO or IAASA, which are also presented in Table 5[8].

	1990	2010	Cutback(%)	Bubble
R95	647	621	-4	26
R97	647	695	+7	-48
R99	647	575	-12	72
IIASA98	647	475	-36	172
IEA98	595	519	-15	76
IEO00	647	448	-44	199

Table 5. Alternative data for Russian carbon emissions (MtC).
Sources: UNFCCC (2000), Victor (1998), Baron (1999), DOE (2000).

It should be noted that the projections for carbon emissions of the Annex I EE/FSU region are changing quickly. Baron (1999) reports 156.5 MtC as the total "hot air" estimate based on the IEA98 projections. The U.S. Department of Energy projected 374 MtC of "hot air" in their 1999 publication. Higher Russian economic growth decreased their projections to 318 MtC in 2000 (DOE, 2000). The discrepancy in carbon emission projections is mostly due to variability of Russian GDP growth numbers reported in Table 6.

1996	1997	1998	1999	2000 (6 months)
-3.4	0.9	-4.9	3.2	5.5

Table 6. Russian GDP growth.
Source: Russian Economic Trends (2000)

In our calibration we used the above mentioned rates for 1996-2000 and the following FSU GDP growth rates for 2000-2010: 2% for "low growth", 4% for "reference growth", and 5.3% for "high growth". The results for carbon emissions in Russia and FSU are reported in Table 7. Our "low" scenario is close to the 2000 *International Energy Outlook* projections, our "reference case" is comparable with Russian pessimistic projection, and our "high" scenario eliminates "hot air" completely.

[8] For the IEO00 scenario, we estimate Russian emissions as 75.8% of the Annex I FSU data (DOE, 2000). For the IEA98 scenario, we estimate the size of the Russian "bubble" as 48.4 of the total excess reported in Baron (1999).

	1990	Target	2010	Cutback(%)	Bubble
Low growth					
Russia	647	647	448	-44	199
FSU	1026	1005	742	-35	263
High growth					
Russia	647	647	649	0.3	-2
FSU	1026	1005	1008	0.3	-3
Reference case					
Russia	647	647	568	-14	79
FSU	1026	1005	901	-11.5	104

Table 7. Projected Russian and FSU emissions (MtC).

4 The GTAP-EG Model

The model employed in this paper is based on the GTAP-EG dataset (Rutherford and Paltsev, 2000). The world is divided into regions. The regions and sectors of the model are presented in Table 8. An algebraic representation of the model is reported in Appendix 3. Each region incorporates markets for non-energy goods, C, electricity, E, and non-electric energy, N. Non-electric energy includes: oil, gas and coal. Crude oil may be produced domestically or imported, and it is then refined prior to delivery as an input to production and final demand. Electricity is not traded and is produced using coal, oil, gas or non-fossil inputs. Final energy products are supplied as inputs both to production and to final demand.

Consumption in each region is associated with utility maximization by a representative agent subject to a budget constraint. The agent supplies primary factors (capital, K, labor, L, and energy resources, R) to non-energy and energy sectors. Factor income of each representative agent is then allocated to the purchase of energy (E and N), non-energy goods (C), and investment (I). Regions are connected with the global economy through trade in energy and non-energy goods. Energy trade involves primarily crude oil and coal which can be exported or imported in international markets.

The flows are implemented in the model in the following way. In the model there are three types of produced commodities, fossil-fuel, non-fossil fuel commodities, and electricity. The model assumes that goods produced in different regions are qualitatively distinct (Armington, 1969). This implies that trade in goods is represented as flows between pairs of countries rather than from individual countries and an integrated global market. Every bilateral trade flow requires its own transportation services. Primary factors in each region include labor, capital and fossil-fuel resources. Labor is mobile within domestic borders but cannot move between regions. Capital can be global or region-specific. Natural resources are sector-specific.

In the GTAP-EG model, an economy in region r consists of three production blocks. The block Y_{ir} is related to production, where fossil-fuel production has a different structure from other production sectors. A production block for Armington supply, A_{ir}, represents an aggregation between domestic and import varieties and across imports from different trading partners. Armington supply is used then for private consumption and as an intermediate input to production. A production block yt describes the provision of international transport services. In each region the representative agent (described by a block RA_r) depicts a collective decision process for allocating income to households and to a government.

Region	Symbol	Sector	Symbol
Annex B:			
United States	USA	Energy-Intensive Sectors	EIS
Canada	CAN	Other manufactures and Services	Y
Europe	EUR	Coal	COL
Japan	JPN	Petroleum and coal products (refined)	OIL
Australia and New Zealand	OOE	Crude oil	CRU
Former Soviet Union	FSU	Natural gas	GAS
Non-Annex B:		Electricity	ELE
China	CHN	Savings Good	CGD
India	IND		
Brazil	BRA		
Other Asia	ASI		
Mexico + OPEC	MPC		
Rest of world	ROW		

Table 8. Regions and Sectors

In the GTAP-EG model, an economy in region r consists of three production blocks. The block Y_{ir} is related to production, where fossil-fuel production has a different structure from other production sectors. A production block for Armington supply, A_{ir}, represents an aggregation between domestic and import varieties and across imports from different trading partners. Armington supply is used then for private consumption and as an intermediate input to production. A production block yt describes the provision of international transport services. In each region the representative agent (described by a block RA_r) depicts a collective decision process for allocating income to households and to a government.

Regions may apply domestic carbon taxes. Carbon tax revenue is collected by the representative agent in each region. Within this model, the carbon tax policy is equivalent to an emission permit system where the permit price coincides with the carbon tax. There are also taxes on output, ty, intermediate inputs, ti, consumption, tc, export, tx, and import, tm. Figure 4 depicts the structure of the model.

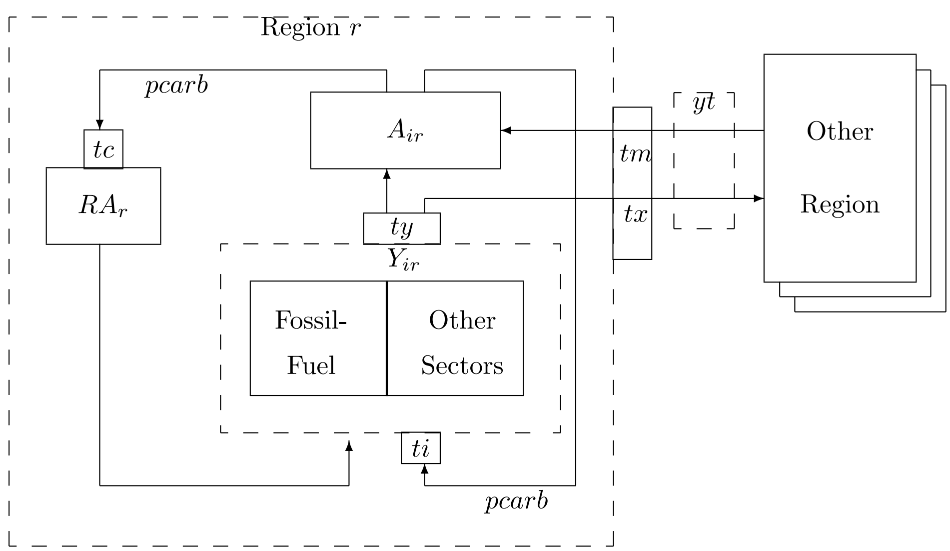

Fig. 4. Structure of the GTAP-EG model.

Fossil fuel production activities include extraction of crude, gas, and coal. Production has the structure shown in Figure A.1 in Appendix 2, where a value to the right of the arc represents an elasticity. Fossil fuel output ($y(xe)$, where xe is one type of exhaustible energy: crude, gas, coal) is produced as an aggregate of a resource input ($pr(xe)$) and a non-resource input composite. The non-resource input for the production is a fixed - coefficient (Leontief) composite of labor (pl) and the Armington aggregation ($pa(i)$) of domestic and imported intermediate input from a production sector i. The elasticity of substitution between pa and pl equals zero ($id : 0$), which characterizes a Leontief composite. The elasticity of substitution ($s : esub\_es$) between the resource input and the non-resource input composite depends on the value share of resource inputs in fossil fuel supply.

Non-fossil fuel production (including electricity and refining) has a different structure. Figure A.2 illustrates the nesting and typical elasticities employed in production sectors other than fossil fuels. Output is produced with fixed-coefficient (Leontief) inputs of intermediate non-energy goods and an energy-primary factor composite. The energy-primary factor composite is a constant-elasticity of substitution (CES) function with elasticity = 0.5. Primary factor inputs of labor and capital are aggregated through a Cobb-Douglas production function ($va : 1$). The energy composite is a CES function of electricity versus other energy inputs, coal versus liquid fuels, and oil versus gas.

Armington aggregation activity generates intermediate demand for production and final demand for consumption as a mix of domestic and imported goods as imperfect substitutes. We assume that the domestic-imports elasticity of substitution (d) equals to four, while the elasticity of substitution among import sources (m) equals to eight. Imports from every region require transportation services (pt) which are implemented as shown in Figure A.3 for region S. The international transport services are assumed to be a Cobb-Douglas composite of goods provided in the domestic markets in each region. Final demand has the structure shown in Figure A.4. Utility in each country is a constant elasticity aggregate of non-energy consumption and energy. The non-energy composite is in turn a Cobb-Douglas aggregate of different goods while final energy is a Cobb-Douglas aggregate of electricity, oil, gas, and coal.

We take 2010 as a baseyear for our comparative statics studies. In order to analyse the effects of different emission trading regimes, we set up the following scenarios:

Bau - Business as usual. The Kyoto Protocol is not ratified;

Notrade - The Kyoto Protocol is ratified with no carbon permit trading;

Trade - The Kyoto Protocol is ratified with unrestricted carbon permit trading among the Annex B countries;

Cap - The Kyoto Protocol and the EU Proposal are ratified. Russia complies with the agreement;

Nocomply - The Kyoto Protocol and the EU proposal are ratified. Russia does not comply with the Kyoto agreement;

There are certain limitations to our study. The economic effects of JI and CDM projects crucially depend on how the rules of those projects are structured (and they are undefined yet), therefore, we focus our attention on emission trading. In every scenario we assume that emission trading does not involve any transaction costs. We also assume that the "however" clause of the EU proposal is not going to be adopted due to impossibility of verification of domestic abatement that would happen in the absence of the Kyoto Protocol. In addition, the "however" clause can be viewed as relaxation of a ceiling. Therefore, depending on interpretation of the clause, the results of this case are going to lie somewhere between our "Trade" and "Cap" scenarios. We also do not consider potential carbon sinks, such as forests or soils. The Kyoto Protocol defines a country's carbon emissions as "emissions by sources minus removals by sinks". A recent IIASA study by Nilsson *et al* (2000) shows that there is no reliable method available to verify net carbon emissions. Their estimates of Russia's net emissions in 1990 range from -155 to +1299 MtC due to the huge uncertainty of carbon sinks. They conclude that Annex B countries will not be able to verify their Kyoto targets at the country level.

5 Numerical Results

The major results of our numerical simulations are provided in Appendix 4. Our first conclusion is that free trade in carbon permits increases welfare in almost all Annex B regions and keeps welfare in the non-Annex B countries virtually the same as in the scenario with no trading. Table 9 summarizes the results for the Annex B regions.

	USA	CAN	EUR	JPN	OOE	FSU
Reference case						
Trade	0.2	0.7	0.0	0.6	0.0	5.5
Cap	0.0	0.3	-0.1	0.2	0.0	1.7
Nocomply	0.0	0.2	-0.1	0.2	0.0	0.1
Low growth						
Trade	0.3	1.0	0.0	0.7	0.1	6.9
Cap	0.0	0.3	-0.1	0.2	0.0	1.9
Nocomply	0.0	0.2	-0.1	0.2	0.0	0.1
High growth						
Trade	0.1	0.5	0.0	0.6	0.0	4.0
Cap	0.0	0.3	-0.1	0.2	0.1	1.4
Nocomply	0.0	0.2	-0.1	0.2	0.1	0.1

Table 9. Change in welfare (%) in comparison with no trading regime.

The EU proposed limited trade is still better for the Annex B countries than no trading. However, the gains in welfare are substantially lower than in the case of unrestricted trade. It is interesting to note that the countries with high abatement requirements, Japan, Canada, and USA, are better-off when FSU grows slowly because they have access to a greater amounts of cheap "hot air". Noncompliance by Russia with the Kyoto Protocol goals is inferior for them to any trading regime because Russia loses its opportunity to earn at least something on the sales of emissions rights. It should be noted that if the "hot air" is completely removed from the market, then OOE and EUR became sellers of carbon permits.

The welfare results presented above are mainly determined by the regional marginal abatement costs, which are equal to \$428 for Japan, \$198 for Canada, \$180 for USA, \$109 for Europe, \$73 for the OOE region (Australia and New Zealand), and \$11 for FSU in the high growth scenario. In the other scenarios, the cost for FSU is zero because they are not required to abate.

The world carbon permit prices in the case of trading are presented in Table 10. The EU proposal leads to higher world prices, suggesting that the proposal acts as a ceiling on supply of permits. The more rapid the Russian growth, the higher the permit price, because the absence of "hot air" in the market increases the world price. Noncompliance by Russia increases the price even more in every scenario because in this case Russia is not supplying its cheap permits to the market.

	Trade	Cap	Nocomply
Reference	90	140	155
Low	64	137	155
High	105	142	155

Table 10. World permit price, 1995 \$ per ton of carbon.

Table 11 presents the FSU and the total world carbon emissions for different scenarios. It shows an interesting result, which has not been mentioned previously in the literature. If the Kyoto Protocol were introduced with no emission trading, emissions in Russia would go up in comparison to the business-as-usual case. The same effect would happen in Russia in the case of restricted emission trading. This increase is due to so-called carbon leakage, which can occur through a relocation of carbon intensive industries due to reduced Annex B competitiveness, lower producer prices of fossil fuels in the world markets, or changes in income due to changes in terms of trade. There are studies estimating the increase in carbon emissions by the non-Annex B countries as a result of the Kyoto agreement (Felder and Rutherford, 1993; Weyant, 1999; Burniaux and Martins, 2000), and on the leakage induced by a particular Annex B region (Paltsev, 2000).

	Bau	Notrade	Trade	Cap	Nocomply
Reference case					
FSU	0.901	0.957	0.639	0.957	0.962
Total	7.794	6.871	6.918	6.915	6.876
Low growth					
FSU	0.742	0.787	0.572	0.791	0.792
Total	7.634	6.701	6.982	6.752	6.705
High growth					
FSU	1.008	1.005	0.683	0.954	1.076
Total	7.900	6.929	6.900	6.924	6.990

Table 11. The FSU and total world carbon emissions (BtC).

Unrestricted emission trading leads to an increase in total carbon emissions and to a decrease in the level of emissions in Russia. The Annex B countries emit more due to their access to permits that are cheaper than domestic abatement activities. Russia finds it profitable to cut down domestic emissions in order to increase emission permit export.

Introduction of the cap decreases total emissions, but the reduction is small because of the above mentioned carbon leakage to Russia. Therefore, the declared EU goal of decreased total emissions is unlikely to be achieved with the proposed ceiling. Noncompliance by Russia does not significantly change the total level of carbon emissions except in the high growth scenario. Note also that noncompliance by Russia decreases the total carbon emissions if Russia has "hot air". This is again due to the fact that the other Annex B countries do not have access to cheap "hot air" if Russia is not going to ratify the Kyoto Protocol (and, as such, is excluded from the Annex B emission trading).

Despite the fact that restricted trade is still better for Russia than the no trading scenario because of availability of some "hot air" and an increase in permit price, the best scenario for Russia is free trade. It results in higher welfare and lower domestic emissions. From the point of the Kyoto goal, free trade will make Russia abate more.

The total world carbon emissions follow the same pattern as the numbers for the Annex B regions. It should be noted that in comparison to the *International Energy Outlook* projections, our simulations underestimate growth in non-Annex B emissions in all scenarios. However, non-Annex B growth does not change the results qualitatively and our conclusions are the same.

The manner in which Europe is represented in the economic analysis of emission trading will influence the results. If the EU and its associates (EUA) would decide to act separately then they both gain. The EU gains due to their access to cheaper permits. The EUA region gains from a possibility of trading their cheap permits. Table 12 presents the results for change in welfare in different trading regimes for the case when the EU and its associates (EUA) are represented separately.

	USA	CAN	EUR	EUA	JPN	OOE	FSU
United							
Trade	0.2	0.7	0.0	-	0.6	0.0	5.5
Cap	0.0	0.3	-0.1	-	0.2	0.0	1.7
Nocomply	0.0	0.2	-0.1	-	0.2	0.0	0.1
Separate							
Trade	0.2	0.7	0.2	1.1	0.6	0.0	5.5
Cap	0.0	0.1	0.0	0.7	0.2	0.1	2.0
Nocomply	0.0	0.0	0.0	0.8	0.2	0.1	0.0

Table 12. Change in welfare (%) in comparison with no trading regime in the case of the united and separate EE/EU region.

The Kyoto Protocol is subject to ratification by the signatory parties. It will enter into force after not less than 55 parties, incorporating Annex B Parties which accounted in total for at least 55% of the total carbon dioxide emissions for 1990 from that group, have ratified it. As of today, the Protocol is still not ratified by any Annex B country. The EU proposal makes it even harder to ratify the protocol due to welfare losses. In 1990, the Annex B regions had the following shares of carbon emissions: the USA - 36%, the EU and associates - 30%, Russia and Ukraine - 22%, Japan - 8%, Canada - 3%, Australia and New Zealand (OOE) - 2%.

Russian nonratification of the protocol will not prevent it from entering into force. As seen from the modeling results, noncompliance with the Kyoto goals makes Russia worse off. It follows from the above mentioned shares that without the USA and Russia the Protocol will not be viable. Then the strategy for Russia is to encourage doubt as to the effectiveness of the EU proposal. As long as the USA perceives the proposal as harmful to itself, the Kyoto Protocol will not be ratified. Russia can encourage the USA think in this way because free trade and cheap Russian permits make the USA better off. The current position of the USA (and the UMBRELLA group) on the rules of emissions trading is in accordance with this result.

There is an additional dynamic aspect of the emission reduction negotiation process. Access to “hot air” would allow some parties to meet their commitments while continuing their carbon-intensive emission trends. This would reduce their commitments for the period after 2012. Also, political constraints may be a serious threat for significant domestic abatement activities.

Why is the EU proposal still in place even if it is clear that it would lead to welfare losses in every Annex B region? Hourcane (2000) mentions that the European countries have higher environmental concerns. They introduced the proposal in the hope that it would lead to a substantial reduction in carbon emissions. In addition, the EU hopes that carbon tax revenue can be used for other European priorities such as harmonization of fiscal policy, double dividend issue (which may lower a labor tax in Europe), and regulation of the transportation sector. The EU perceives a presence of “hot air” and the resulting low price for carbon permits as a threat to their environmental agenda.

What is in the Kyoto Protocol for Russia? Russia, with its emissions of 647 MtC in 1990, is the second highest emitter of energy-related CO_2. Obviously, ability to trade its emission permits is crucial for Russia. It undoubtedly gains from the possibility of carbon emission trading as it has plenty of permits to sell virtually at no cost to itself. However, some authors (UNFCCC, 2000) argue that the actual cost for Russia is very high and it is paid by its population experiencing sharp decline in living standards due to the difficulties of economic transition. Emission trading would take into account the Russia’s real contribution in reducing carbon emissions into atmosphere which has taken place since 1990. In many cases, the usage of the term “hot air” reflects political hostility to the Kyoto allocation of carbon permits for Russia. It does not matter if somebody calls it “hot air” or “carbon bubble”, ratification of the protocol with a possibility for unrestricted trade is the best option for Russia.

6 Conclusion

The Kyoto Protocol sets the carbon emission targets for 2008-2012 for the major emitting countries and establishes the possibility for carbon emission trading. However, the exact rules of trading are being negotiated. Most projections show that Russia and Ukraine will have emission targets in excess of their anticipated emissions. This excess is called "carbon bubble" or "hot air". In principle, "carbon bubbles" may exist in some other European countries but political reasons will prevent them from the sale of their "bubbles".

The estimates of Russian "hot air" vary over time with the economic performance of Russia. Also, different projecting agencies have different views on the future paths of carbon intensity and energy intensity. While the "hot air" estimates range from 150 to 500 MtC, most of the US and European agencies project the difference between actual and targeted emissions of Eastern Europe and FSU in 2010 as 300-350 MtC, with the Russian share being 170-200 MtC. The other Annex B countries are expected to cut their emissions by 810-850 MtC, which results in the total Annex B decrease in carbon emissions by 500-550 MtC, or 12-15 percent of the Annex B emissions in 2010.

Russian national estimates of the difference between its actual and targeted emissions in 2010 range from 0 to 72 MtC, which corresponds to 0-12 percent of the Russian targeted emissions in 2010. Recent economic growth in Russia will lower the estimate of the "carbon bubble" even further. This implies a greater Kyoto-required decrease in the total Annex B emissions.

The main contribution of this paper is the quantitative assessment of the level of emissions and welfare costs in different scenarios of carbon permit trading. If the Kyoto Protocol is implemented, unrestricted emissions trading will improve welfare in all Annex B countries in comparison to the no trading scenario but the total world emissions rise. Such a free trade scenario leads to lower emissions in Russia than in the case when the Kyoto Protocol is not ratified or the protocol is ratified with no trading allowed. Unrestricted trade results in big welfare gains (5.5 percent) in Russia.

The EU proposal for a ceiling on emission trading is motivated by their desire to achieve lower total world emissions. However, the proposal implies substantial welfare losses for all Annex B parties. In addition, carbon leakage to Russia would mean that emissions would not be significantly reduced.

Without implementing unrestricted trade, Russia and Ukraine have an incentive not to ratify the protocol. However, they alone cannot impose a credible threat of removing themselves from the Kyoto agreement if the ceiling were imposed. An alliance with the other signatory countries who experience high mitigation costs and who want to exploit the full efficiency of free trade in carbon permits makes adoption of the ceiling proposal questionable. Indeed, with the possibility of exchanging excess carbon emissions, all countries would find it profitable to ratify the protocol.

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Appendix 1. Emission Limits under the Kyoto Protocol

Appendix 1 contains the list of Annex B countries and their emission limits as a percentage of a base year emissions according to the Kyoto Protocol (UNFCCC, 1997).

Country	%change in emissions
Australia	108
Austria	92
Belgium	92
Bulgaria*	92
Canada	94
Croatia*	95
Czech Republic*	92
Denmark	92
Estonia*	92
European Community	92
Finland	92
France	92
Germany	92
Greece	92
Hungary*	94
Iceland	110
Ireland	92
Italy	92
Japan	94
Latvia*	92
Liechtenstein	92
Lithuania*	92
Luxembourg	92
Monaco	92
Netherlands	92
New Zealand	100
Norway	101
Poland*	94
Portugal	92
Romania*	92
Russian Federation*	100
Slovakia*	92
Slovenia*	92
Spain	92
Sweden	92
Switzerland	92
Ukraine*	100
United Kingdom	92
United States of America	93

* Countries that are undergoing the process of transition to a market economy.

Appendix 2. Structure of the GTAP-EG model blocks

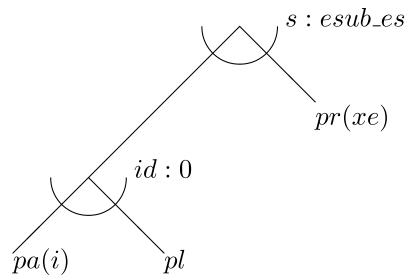

Fig. A.1. Fossil fuel production

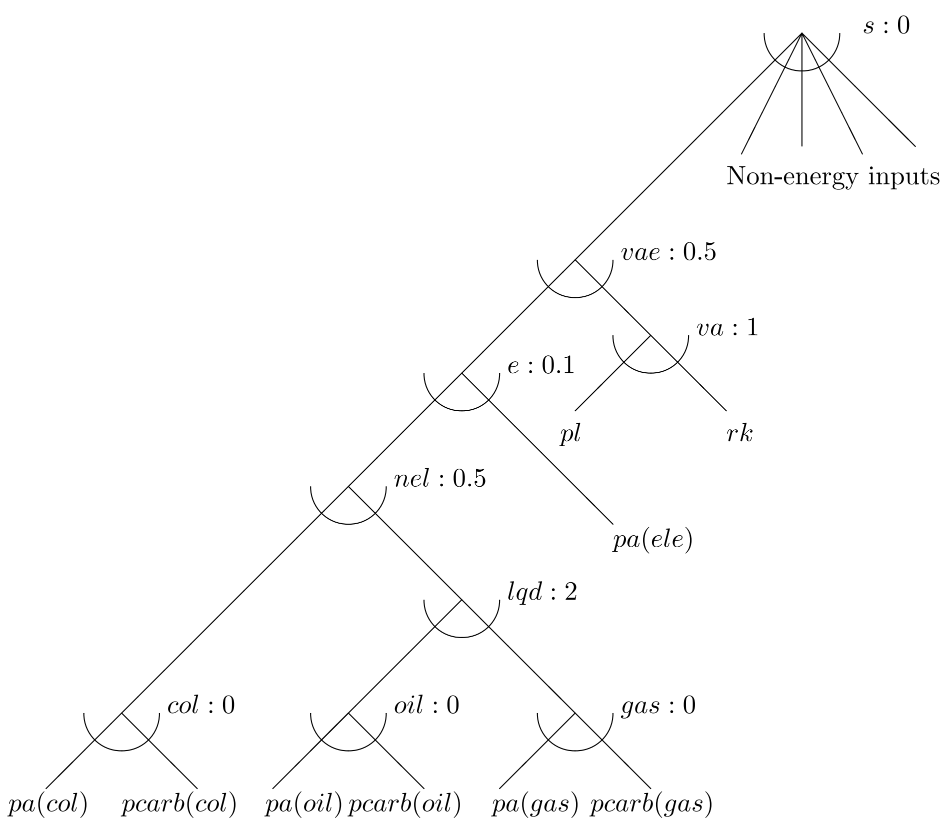

Fig. A.2. Non-fossil fuel production

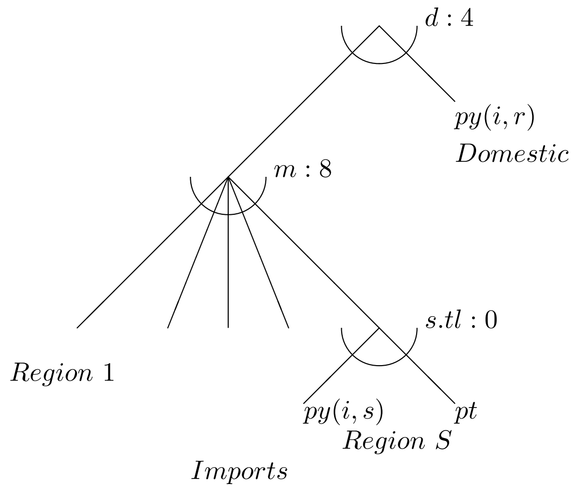

Fig. A.3. Armington aggregation

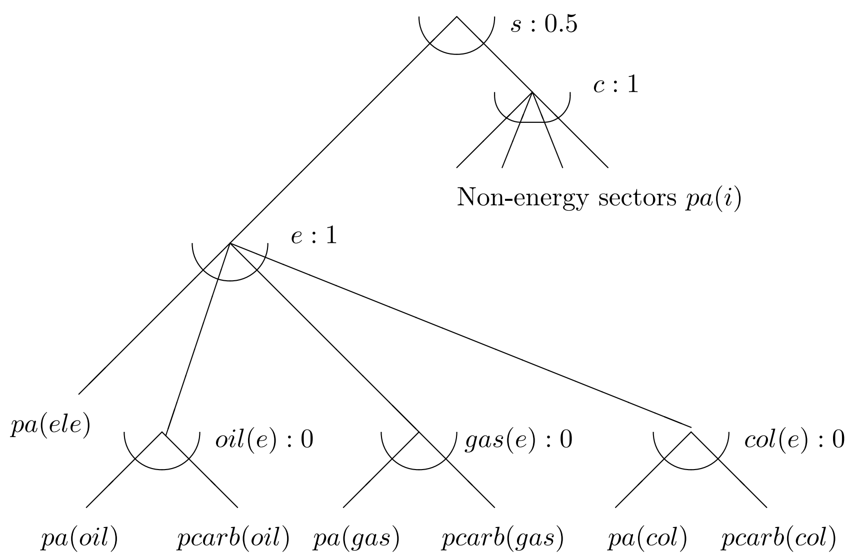

Fig. A.4. Final demand

Appendix 3: Algebraic Model Summary

A.1 Zero Profit Conditions

1. Production of goods except fossil fuels:

$$\Pi^Y_{ir} = p_{ir} - \sum_{j\notin EG} \theta_{jir}\, p^A_{Yjr} - \theta^{KLE}_{ir}\left[\theta^E_{ir}\, p^{E\;1-\sigma_{KLE}}_{ir} + (1-\theta^E_{ir})\left(w_r^{\alpha^L_{jr}}\, v_r^{\alpha^K_{jr}}\right)^{1-\sigma_{KLE}}\right]^{\frac{1}{1-\sigma_{KLE}}} = 0 \qquad i \notin FF$$

2. Production of fossil fuels:

$$\Pi^Y_{ir} = p_{ir} - \left[\theta^Q_{ir}\, q_{ir}^{1-\sigma_Q} + (1-\theta^Q_{ir})\left(\theta^{FF}_{Lir}\, w_r + \theta^{FF}_{Kir}\, v_r + \sum_j \theta^{FF}_{jir}\, p^A_{Yjr}\right)^{1-\sigma_Q}\right]^{\frac{1}{1-\sigma_Q}} = 0 \qquad i \in FF$$

3. Sector-specific energy aggregate:

$$\Pi^E_{ir} = p^E_{ir} - \left\{\theta^{ELE}_{ir}\, p^{A^{1-\sigma_{ELE}}}_{\{Y,ELE,r\}} + (1-\theta^{ELE}_{ir})\left[\theta^{COA}_{ir}\, p^{A^{1-\sigma_{COA}}}_{\{Y,COA,r\}} + (1-\theta^{COA}_{ir})\left(\prod_{j\in LQ} p^{A^{\beta_{jir}}}_{Yjr}\right)^{1-\sigma_{COA}}\right]^{\frac{1-\sigma_{ELE}}{1-\sigma_{COA}}}\right\}^{\frac{1}{1-\sigma_{ELE}}} = 0$$

4. Armington aggregate:

$$\Pi^A_{dir} = p^A_{dir} - \left[\left(\theta^A_{dir}\, p_{ir}^{1-\sigma_A} + (1-\theta^A_{dir})\, p^{M^{1-\sigma_A}}_{ir}\right)^{\frac{1}{1-\sigma_A}} + t^{CO2}_r\, a^{CO2}_i\right] = 0$$

5. Aggregate imports across import regions:

$$\Pi^M_{ir} = p^M_{ir} - \left(\sum_s \theta^M_{isr}\, p^{1-\sigma_M}_{is}\right)^{\frac{1}{1-\sigma_M}} = 0$$

6. Household consumption demand:

$$\Pi^C_r = p^C_r - \left(\theta^E_{Cr}\, p^{E^{1-\sigma_{EC}}}_{Cr} + (1-\theta^E_{Cr})\left[\prod_{i\notin EG} p^{A^{\gamma_{ir}}}_{Cir}\right]^{1-\sigma_{EC}}\right)^{\frac{1}{1-\sigma_{EC}}} = 0$$

7. Household energy demand:

$$\Pi^E_{Cr} = p^E_{Cr} - \left\{\theta^E_{\{ELE,C,r\}}\, p_{ELE,r}^{1-\sigma_{ELE,C}} + (1-\theta^E_{\{ELE,C,r\}})\left[\left(\sum_{i\in EG\setminus\{ELE\}} (\theta^E_{iCr}\, p^{A^{1-\sigma_{NELE}}}_{Cir})\right)^{\frac{1}{1-\sigma_{NELE}}}\right]^{1-\sigma_{ELE,C}}\right\}^{\frac{1}{1-\sigma_{ELE,C}}} = 0$$

A.2 Market Clearance Conditions

8. Labor:

$$\overline{L}_r = \sum_i Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial w_r}$$

9. Capital:

$$\overline{K}_r = \sum_i Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial v_r}$$

10. Natural resources:

$$\overline{Q}_{ir} = Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial q_{ir}} \qquad i \in FF$$

11. Good markets:

$$Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial p_{ir}} = \sum_{dj} A_{djr} \frac{\partial \Pi_{djr}^A}{\partial p_{ir}} + \sum_s M_{is} \frac{\partial \Pi_{is}^M}{\partial p_{ir}}$$

12. Sector specific energy aggregate:

$$E_{ir} = Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial p_{ir}^E}$$

13. Import aggregate:

$$M_{ir} = \sum_d A_{dir} \frac{\partial \Pi_{dir}^A}{\partial p_{ir}^M}$$

14. Armington aggregate:

$$A_{dir} = \sum_j Y_{jr} \frac{\partial \Pi_{jr}^Y}{\partial p_{dir}^A} + C_r \frac{\partial \Pi_r^C}{\partial p_{dir}^A}$$

15. Household consumption:

$$C_r \, p_r^C = (w_r \overline{L}_r + v_r \overline{K}_r + \sum_{j \in FF} q_{jr} \overline{Q}_{jr} + t_r^{CO2} \overline{CO2}_r + p_{CGD,r} \overline{Y}_{CGD,r} + \overline{B}_r$$

16. Aggregate household energy consumption:

$$E_{Cr} = C_r \frac{\partial \Pi_r^C}{\partial p_{Cr}^E}$$

17. Carbon emissions:

$$\overline{CO2}_r = \sum_{di} A_{dir} a_i^{CO_2}$$

Table A.1: Sets

i	Sectors and goods
j	Aliased with I
r	Regions
s	Aliased with r
EG	All energy goods: Coal, crude oil, refined oil, gas and electricity
FF	Primary fossil fuels: Coal, crude oil and gas
LQ	Liquid fuels: Crude oil, refined oil and gas
d	Demand categories: Y = intermediate, C = household and I = investment

Table A.2: Activity variables

Y_{ir}	Production in sector *i* and region *r*
E_{ir}	Aggregate energy input in sector *i* and region *r*
M_{ir}	Aggregate imports of good *i* and region *r*
A_{dir}	Armington aggregate for demand category *d* of good *i* in region *r*
C_r	Aggregate household consumption in region *r*
E_{Cr}	Aggregate household energy consumption in region *r*

Table A.3: Price variables

p_{ir}	Output price of good *i* produced in region *r* for domestic market
p_{ir}^E	Price of aggregate energy in sector *i* and region *r*
p_{ir}^M	Import price aggregate for good *i* imported to region *r*
p_{dir}^A	Price of Armington aggregate for demand category *d* of good *i* in region *r*
p_r^C	Price of aggregate household consumption in region *r*
p_{Cr}^E	Price of aggregate household energy consumption in region *r*
w_r	Wage rate in region *r*
v_r	Price of capital services in region *r*
q_{ir}	Rent to natural resources in region *r* ($i \in FF$)
t_r^{CO2}	CO_2 tax in region *r*

Table A.4: Cost shares

q_{jir}	Share of intermediate good *j* in sector *i* and region *r* (i∉FF)
q_{ir}^{KLE}	Share of KLE aggregate in sector *i* and region *r* (i∉FF)
q_{ir}^{E}	Share of energy in the KLE aggregate of sector *i* and region *r* (i∉FF)
a_{ir}^{T}	Share of labor (*T*=*L*) or capital (*T*=*K*) in sector *i* and region *r* (i∉FF)
q_{ir}^{Q}	Share of natural resources in sector *i* of region *r* (i∈FF)
q_{Tir}^{FF}	Share of good *i* (*T*=*i*) or labor (*T*=*L*) or capital (*T*=*K*) in sector *i* and region *r* (i∈FF)
q_{ir}^{ELE}	Share of electricity in energy demand by sector *i* in region *r* (i∉FF)
q_{ir}^{COA}	Share of coal in fossil fuel demand by sector *i* in region *r*
b_{jir}	Share of liquid fossil fuel *j* in liquid fossil fuel demand by sector *i* in region *r* (i∉FF, j∈LQ)
q_{isr}^{M}	Share of imports of good *i* from region *s* to region *r*
q_{dir}^{A}	Share of domestic variety *i* in Armington aggregate for demand category *d* in region *r*
q_{Cr}^{E}	Share of energy in aggregate household consumption in region *r*
g_{ir}	Share of non-energy good *i* in non-energy household consumption demand in region *r*
$q_{ELE,C,r}^{E}$	Share of electricity in aggregate household energy consumption in region *r*
q_{iCr}^{E}	Share of non-electric energy good *i* in the non-electric household energy consumption in region *r*

Table A.5: Endowments and emissions coefficients

$\overline{L}_r$	Aggregate labor endowment for region *r*
$\overline{K}_r$	Aggregate capital endowment for region *r*
$\overline{Q}_{ir}$	Endowment of natural resource *i* for region *r* (i∈FF)
$\overline{B}_r$	Balance of payment surplus in region r (note: $\sum_r \overline{B}_r = 0$)
$\overline{CO_2}_r$	Endowment of carbon emission rights in region *r*
$a_i^{CO_2}$	Carbon emissions coefficient for fossil fuel *i* (*iÎ FF*) in demand category *d* of region *r*

Appendix 4. Numerical results

Carbon emissions (BtC)

Reference case

	bau	notrade	trade	cap	nocomply
USA	1.861	1.279	1.483	1.356	1.325
CAN	0.173	0.118	0.139	0.125	0.125
EUR	1.488	1.213	1.260	1.160	1.145
JPN	0.429	0.295	0.378	0.313	0.313
OOE	0.109	0.088	0.085	0.083	0.083
FSU	0.901	0.957	0.639	0.957	0.962
CHN	1.140	1.170	1.173	1.170	1.170
IND	0.264	0.268	0.268	0.268	0.268
BRA	0.099	0.100	0.100	0.100	0.100
ASI	0.318	0.329	0.330	0.329	0.329
MPC	0.545	0.566	0.574	0.565	0.566
ROW	0.469	0.490	0.491	0.490	0.491
annnexB	4.960	3.948	3.983	3.993	3.952
non-anB	2.834	2.923	2.935	2.921	2.924
TOTAL	7.794	6.871	6.918	6.915	6.876

High growth

	bau	notrade	trade	cap	nocomply
USA	1.861	1.279	1.443	1.353	1.325
CAN	0.173	0.118	0.135	0.125	0.125
EUR	1.488	1.213	1.236	1.161	1.145
JPN	0.429	0.295	0.373	0.313	0.313
OOE	0.109	0.088	0.083	0.083	0.083
FSU	1.008	1.005	0.683	0.954	1.076
CHN	1.140	1.173	1.176	1.174	1.170
IND	0.264	0.269	0.269	0.269	0.268
BRA	0.099	0.101	0.100	0.100	0.100
ASI	0.318	0.330	0.333	0.330	0.329
MPC	0.545	0.569	0.578	0.571	0.566
ROW	0.469	0.491	0.494	0.493	0.491
annexB	5.067	3.996	3.952	3.988	4.066
non-anB	2.834	2.933	2.949	2.936	2.924
TOTAL	7.900	6.929	6.900	6.924	6.990

Low growth

	bau	notrade	trade	cap	nocomply
USA	1.861	1.279	1.564	1.356	1.325
CAN	0.173	0.118	0.146	0.125	0.125
EUR	1.488	1.213	1.310	1.165	1.145
JPN	0.429	0.295	0.389	0.313	0.313
OOE	0.109	0.088	0.090	0.083	0.083
FSU	0.742	0.787	0.572	0.791	0.792
CHN	1.140	1.170	1.165	1.169	1.170
IND	0.264	0.268	0.268	0.268	0.268
BRA	0.099	0.100	0.100	0.100	0.100
ASI	0.318	0.329	0.328	0.329	0.329
MPC	0.545	0.566	0.565	0.565	0.566
ROW	0.469	0.490	0.486	0.490	0.491
annexB	4.800	3.779	4.071	3.832	3.782
non-anB	2.834	2.923	2.911	2.920	2.924
TOTAL	7.634	6.701	6.982	6.752	6.705

Welfare

Reference case

	notrade	trade	cap	nocomply
USA	0.993	0.995	0.993	0.993
CAN	0.980	0.987	0.983	0.982
EUR	0.998	0.998	0.997	0.997
JPN	0.992	0.998	0.994	0.994
OOE	0.991	0.991	0.991	0.991
FSU	0.992	1.047	1.009	0.993
CHN	0.999	1.000	0.999	0.999
IND	1.002	1.002	1.002	1.002
BRA	1.001	1.001	1.001	1.001
ASI	1.001	1.001	1.001	1.001
MPC	0.991	0.992	0.992	0.991
ROW	0.997	0.998	0.997	0.997

High growth

	notrade	trade	cap	nocomply
USA	0.993	0.994	0.993	0.993
CAN	0.980	0.985	0.983	0.982
EUR	0.998	0.998	0.997	0.997
JPN	0.992	0.998	0.994	0.994
OOE	0.990	0.990	0.991	0.991
FSU	0.992	1.032	1.006	0.993
CHN	0.999	1.000	1.000	0.999
IND	1.002	1.002	1.002	1.002
BRA	1.001	1.001	1.001	1.001
ASI	1.001	1.002	1.001	1.001
MPC	0.990	0.990	0.990	0.991
ROW	0.997	0.998	0.997	0.997

Low growth

	notrade	trade	cap	nocomply
USA	0.993	0.996	0.993	0.993
CAN	0.980	0.990	0.983	0.982
EUR	0.998	0.998	0.997	0.997
JPN	0.992	0.999	0.994	0.994
OOE	0.991	0.992	0.991	0.991
FSU	0.992	1.061	1.011	0.993
CHN	0.999	1.000	0.999	0.999
IND	1.002	1.001	1.002	1.002
BRA	1.001	1.001	1.001	1.001
ASI	1.001	1.001	1.001	1.001
MPC	0.991	0.994	0.992	0.991
ROW	0.997	0.998	0.997	0.997

Permit price

Regional

	ref	hi	low
USA	180.38	180.74	180.38
CAN	198.34	198.90	198.34
EUR	109.18	110.95	109.18
JPN	428.18	429.56	428.18
OOE	73.47	74.59	73.47
FSU	M(0.37)	10.66	M(2.039)

World price

	trade	cap	nocomply
ref	90.08	140.06	154.69
hi	104.63	142.47	154.69
low	64.31	136.80	154.69