



The World's Largest Open Access Agricultural & Applied Economics Digital Library

This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.

Help ensure our sustainability.

Give to AgEcon Search

AgEcon Search

<http://ageconsearch.umn.edu>

aesearch@umn.edu

*Papers downloaded from **AgEcon Search** may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.*

No endorsement of AgEcon Search or its fundraising activities by the author(s) of the following work or their employer(s) is intended or implied.



Global Trade Analysis Project

<https://www.gtap.agecon.purdue.edu/>

This paper is from the
GTAP Annual Conference on Global Economic Analysis
<https://www.gtap.agecon.purdue.edu/events/conferences/default.asp>

A Two-Level Dynamic Game of Carbon emissions Trading Between Russia, China, and Annex B Countries

A. Bernard, A. Haurie, M. Vielle, and L. Viguiier

September, 2002



**Swiss National Centre of Competence (NCCR) “Climate”
Work Package 4: “Climate Risk Assessment”
University of Geneva & Paul Scherrer Institute**

Contact: Prof. Alain B. Haurie

University of Geneva

40, Bld du Pont d’Arve

CH-1211 Geneva, Switzerland.

Phone +41-22-705- 8132

Webpage: <http://ecolu-info.unige.ch/~nccrwp4/>

Copyright © *date* NCCR-WP4. All rights reserved.

No portion of this paper may be reproduced without permission of the authors

A Two-Level Dynamic Game of Carbon Emissions Trading Between Russia, China, and Annex B Countries*

October 22, 2002

A. Bernard^a, A. Haurie^b, M. Vielle^c, L. Viguiier^b

^aMinistère de l'Équipement, des Transports et du Logement

^bFaculty of Economics and Social Sciences, University of Geneva

^cCommissariat à l'Énergie Atomique & University of Toulouse

Abstract

This paper proposes a computable dynamic game model of the strategic competition between Russia and developing countries (DCs), mainly represented by China, on the international market of emissions permits created by the Kyoto protocol. The model uses a formulation of a demand function for permits from Annex B countries and of marginal abatement costs (MAC) in Russia and China provided by two detailed models. GEMINI-E3 is a computable general equilibrium model that provides the data to estimate Annex B demand for permits and MACs in Russia. POLES is a partial equilibrium model that is used to obtain MAC curves for China. The competitive scenario is compared with a monopoly situation where only Russia is allowed to play strategically. The impact of allowing DCs to intervene on the international emissions trading market is thus assessed.

*This work has been undertaken with the support of the NSF-NCCR “climate” grant. We thank Patrick Criqui for providing us with POLES simulations. The views expressed herein, including any remaining errors, are solely the responsibility of the authors.

1 Introduction

The aim of this paper is to propose a computable economic model of the strategic interactions between Russia, also called FSU¹, and Developing Countries (DCs), in particular China, in international markets for carbon emissions permits created by the Kyoto protocol. This model will provide an assessment of the impact of this competition on the pricing of emissions permits. We assume that some DCs will participate in next commitment periods of the Kyoto protocol and be able to sell emissions permits on the international market. We also assume that the rest of the world (Annex B countries) will behave as a passive set of players integrating the emissions permits in their production decisions according to the rules of a time stepped² competitive economic equilibrium. A particular feature of the Kyoto protocol is the large quantity of emissions rights granted to FSU, since they were based on historic levels. Due to the collapse of the traditional industrial sectors in FSU, these emissions rights are now available at no cost to Russia³. The agreement allows Russia to bank these emissions rights and optimize over time their sale on the international market. This feature gives a dynamic structure to this oligopolistic competition for selling emissions permits to Annex B countries. We formalize it as a dynamic multistage game for which we compute an open-loop Nash equilibrium solution [5], [47], [19]⁴. Differential game models have already been used successfully in environmental economics as e.g. in the fishery games⁵ and more recently to analyze the acid rain game [35]. In the Kyoto protocol context A. Loschel and Z. Zhang [34] have analyzed the interactions between Eastern Europe and Russia as a static Cournot model of duopoly, where the two regions simultaneously set their quantity supplied to the permits market by 2010.

The model we propose also includes transaction costs. The transaction cost approach to the theory of the firm was first introduced by Ronald Coase in 1937 in his seminal paper “The Nature of the Firm” [13]. Transaction costs refer to the cost of providing for some good or service through the market rather than from within the firm⁶. Several authors have commented on the potential importance of transaction costs in tradable permits markets [27][43]. The cost-effectiveness of tradable permits systems can adversely be affected by transaction costs due to concentration in the permit market, concentration in the output market, non-profit-maximizing behavior, the pre-existing regulatory environment, and the degree of monitoring and enforcement [43]⁷. In its global formulation our model is similar to [40] except that it does not deal with a spatially distributed pollutant and it has a dynamical two-level structure, where two player compete actively at the upper-level whereas a competitive fringe reacts at the lower level.

The dynamic game model involves only one state variable for each player, namely the stock of emissions permits banked by Russia and the dominant DC, China. The time horizon on which Russia and DCs compete to sell emissions rights to AnnexB countries is 2030. Each player has three control variables that are the rate of permits banking, the amount of permits supplied, and

¹Former Soviet Union.

²This means that the equilibrium is not dynamic and the investment strategies are fixed.

³They are also called *hot air*.

⁴Due to the affine structure w.r.t. the single state variable assures that open-loop solution will also be subgame perfect.

⁵see [33] [28] or [6] as a brief sample of the large literature on the topic.

⁶In “The Problem of Social Cost”, Coase [14] explains that “In order to carry out a market transaction it is necessary to discover who it is that one wishes to deal with, to conduct negotiations leading up to a bargain, to draw up the contract, to undertake the inspection needed to make sure that the terms of the contract are being observed, and so on. More succinctly, transaction costs consist of ex ante and ex post costs. In the market the ex ante costs include the expense of searching for a trading partner, specifying the product(s) to be traded and negotiating the price and contract. The ex post transaction costs are incurred after the contract has been signed but before the entire transaction has been completed. These include late delivery, non-delivery or non-payment and problems of quality control.

⁷See also the U.S. experience on SO₂ allowance trading [31] and RECLAIM Trading Credits for NO_x and SO_x [21].

the emissions abatement levels, respectively. The equilibrium decisions by the two players are driven by the functions describing the demand for permits from Annex B countries and by their respective marginal abatement cost functions. These functions will be themselves obtained from two other models, GEMINI-E3 and POLES respectively. GEMINI-E3 is a Computable General Equilibrium (CGE) model of the world economy[7] that will provide an estimate of the Annex B countries demand law for emissions permits at each period t . POLES is a partial equilibrium model of the world energy system[15] that will be used to estimate abatement cost functions for the two players. With these specifications we compute the Cournot-Nash equilibrium for the dynamic game and compare the solution with the monopoly equilibrium where only Russia is strategically supplying the market to assess the benefits obtained from allowing DCs to compete on the emissions market. In our scenarios, the emissions permits game takes place between Russia and China, knowing that China is likely to be the main exporter of emissions permits in a full global trading regime [22][16][48].

The paper is organized as follows. In Section 2 we recall the fundamental economic elements of the Kyoto protocol. In Section 3, the dynamic game is formulated and the conditions characterizing a Nash equilibrium are given in the form of a nonlinear complementarity problem [23]. In Section 4 we discuss the calibration of the model based on simulations obtained from GEMINI-E3 and POLES models. Section 5 presents the simulation results. This reference scenario is compared with a case where Russia acts as a monopoly in the emissions market. Due to the large uncertainty around parameters values of the model, we proceed to a sensitivity analysis of the results in section 6 to 1) the participation of China in the international effort to curb GHG emissions and 2) transaction costs associated with CMD projects. Finally, Section 7 concludes the paper.

2 The economics of the Kyoto-Marrakech agreement

At the Third Conference of the Parties (COP-3) to the United Nations Framework Convention on Climate Change (UNFCCC), Annex B Parties⁸ committed to reducing, either individually or jointly, their total emissions of six greenhouse gases (GHGs) by at least 5 percent within the period 2008 to 2012, relative to these gases' 1990 levels. The Protocol is subject to ratification by Parties to the Convention.⁹ The Protocol has already been ratified by 77 countries representing 36% of the total CO₂ emissions of Annex B parties in 1990. However, the U.S. withdrawal from the Kyoto Protocol changes dramatically the character of the agreement.¹⁰ In particular, it may put the international market for GHG emissions permits at risk. Using the MIT-EPPA model, Babiker *et al.* [3] estimate that Annex B GHG emissions may increase by around 9% under Marrakech and that the international carbon price might fall below \$5 per ton of carbon if all Russian and Ukrainian hot air were freely traded, and if Annex B countries made full use of the additional Article 3.4 sinks.

In that context, strategic behavior by Russia in an international emissions trading regime limited to Annex B countries (without the U.S.) can be expected. Several authors have looked at the purely static, one period problem of maximizing Russia's rent [12][39][11][3]. In a simple

⁸Annex B refers to the group of developed countries comprising of OECD (as defined in 1990), Russia, and Eastern Europe.

⁹It shall enter into force on the ninetieth day after the date on which not less than 55 Parties to the Convention, incorporating Annex I Parties which accounted in total for at least 55% of the total carbon dioxide emissions for 1990 from that group, have deposited their instruments of ratification, acceptance, approval or accession.

¹⁰Since the withdrawal from international negotiations, the Bush administration is expected to bring a "constructive position" to the ongoing Kyoto Protocol negotiations. On February 14, President Bush has presented a voluntary plan to reduce greenhouse gas (GHG) intensity by 18 percent over the next 10 years. It has been shown that the Bush plan could be easily reached, under realistic hypothesis, without any specific climate change policy implementation [45].

static model assuming myopic behaviors, Russia maximizes in each period its gains from permits selling without taking into consideration future opportunities and constraints (e.g. competition with developing countries) and without having the possibility to bank emissions permits. According to the authors, when Russia is assumed to act as a monopoly, the supply of permits is restricted to approximately 50% compared to the competitive scenario, and the equilibrium price of permits ranges from \$20 to \$60. Manne and Richels consider explicitly banking in simulations made using the MERGE model [36]. They show that it is profitable for concerned countries to defer a substantial share of hot air for later use¹¹. Of course the incentive is higher when the U.S. does not ratify the Kyoto Protocol than when it does. According to their simulations, the sales of hot air would be limited to 50 Mt of carbon in 2010 in the first case, while in the second case most of the hot air would be brought to the market (more than 250 Mt of carbon).

Moreover, even if Russia may envision a monopolistic position in the international markets for tradable emissions permits, it might be soon in competition with DCs via the supply of Clean Development Mechanism (CDM) or even their direct participation in emissions trading. Annex B countries may choose to develop CDM projects in developing countries (DC) rather than importing emissions permits from Russia. In response to these concern, Bernard and Vielle [8] and Bernard *et al.* [9] have considered monopolistic behaviors by Russia in an inter-temporal optimization framework. Assuming a Kyoto Forever scenario through 2040 for Annex B countries (with or without the U.S.) and calibrated on a Computable General Equilibrium Model (GEMINI-E3/EPPA-MIT), these studies show that short run carbon prices (2010) are not very clearly impacted by Russia long run strategy. On the contrary, the carbon price has been observed to be very sensitive to the assumption on CDM potential. In [9], the amount of CDM projects competing in each period of time with Russia's emissions permits is set exogenously and DCs strategic behavior is not modelled. However, one might expect strategic interactions between Russia and DCs in carbon markets. DCs can already participate in abatement policies through CDM and we may expect some DCs to join the international effort to curb GHG emissions in next commitment periods. The model that is presented in this paper shows that joining the international permit market will be an interesting opportunity for these countries and a benefit to Annex B countries.

3 The model

The model has the structure of a Cournot duopoly model with depletable resource stocks representing the banked emissions permits. These stocks can be replenished via an abatement activity. Due to the standard structure á la Cournot and the linearity of the state equations we may assume that the conditions for existence and uniqueness of a Nash equilibrium will be met[42].

3.1 The equations

We use a discrete time model with periods $t = 0, 1, \dots, T$. Each player controls a dynamical system described as follows

Player 1: It is the FSU which benefits from hot air. The following variables and parameters enter into the description of Player 1.

In the above parameters and variable, the time function $h(t)$ is exogenously given. It represents the amount of credited "hot air" emissions abatement at each time t . We assume $h(t) \geq 0$

¹¹Knowing that carbon prices may increase over time, Russia may choose to sell less permits in the short run than is justified in the static models. It may also be desirable for Russia to bank permits in order to avoid, in the very long run, costly domestic abatement policies or costly purchases of permits.

- β_1 : discount factor for player 1
- $x_1(t)$: stock of permits that are banked by player 1 at time t
- $u_1(t)$: permits that are supplied by player 1 at time t
- $h(t)$: “hot air” input for player 1 at time t
- $q(t)$: emissions abatement for player 1 at time t
- $c_1(q_1)$: cost function for emissions abatement
- π_1 : terminal value of the stock of permits

if $t < T$ and $h(T) = 0$. The dynamical system representing Player 1 is defined as follows:

$$\max \quad \sum_{t=0}^{T-1} \beta_1^t [p(t)u_1(t) - c_1(q_1(t))] + \beta_1^T \pi_1 x_1(T) \quad (1)$$

s.t.

$$x_1(t+1) = x_1(t) - u_1(t) + h(t) + q_1(t) \quad (2)$$

$$x_1(0) = 0 \quad (3)$$

$$u_1(t) \geq 0 \quad (4)$$

$$x_1(t) \geq 0. \quad (5)$$

Player 2: It represents Developing countries (typically China) which may develop their own market of emissions rights instead of the CDM scheme. The following variables and parameters enter into the description of Player 2.

- β_2 : discount factor for player 2
- $x_2(t)$: stock of permits that are banked by player 2 at time t
- $u_2(t)$: permits that are supplied by player 2 at time t
- $q_2(t)$: emissions decrease due to Player 2 abatement activities
- $c_2(q_2)$: cost function for emissions abatement
- $u_2(t)$: permits that are supplied by player 2 at time t
- π_2 : terminal value of the stock of permits

The dynamical system representing Player 2 is defined as follows:

$$\max \quad \sum_{t=0}^{T-1} \beta_2^t [p(t)u_2(t) - c_2(q_2(t))] + \beta_2^T \pi_2 x_2(T) \quad (6)$$

s.t.

$$x_2(t+1) = x_2(t) - u_2(t) + q_2(t) \quad (7)$$

$$x_2(0) = 0 \quad (8)$$

$$u_2(t) \geq 0 \quad (9)$$

$$u_2(t) \equiv 0 \quad \forall t \in [0, \theta] \text{ where } \theta < T \quad (10)$$

$$x_2(t) \geq 0. \quad (11)$$

Price of permits: An inverse demand law describes the market clearing price for permits in Annex-1 countries.

$$p(t) = D(u_1(t) + u_2(t)). \quad (12)$$

This demand function is derived from the competitive equilibrium conditions for the Annex B countries in each period.

3.2 The optimality conditions

They are obtained by formulating the first order Nash equilibrium conditions. The search for an equilibrium solution is then formulated as a nonlinear complementarity problem for which efficient algorithms exists. In this application we have use the PATH solver [24].

Player 1: We introduce the Hamiltonian

$$\begin{aligned} H_1(\lambda_1(t+1), x_1(t), u_1(t), q_1(t)) = & \beta_1^t [p(t)u_1(t) - c_1(q_1(t))] + \\ & \lambda_1(t+1)(x_1(t) - u_1(t) + h(t) + q_1(t)) + \\ & \mu_1(t)x_1(t) \end{aligned} \quad (13)$$

where $\lambda_1(t)$ is the costate variable associated with the state equation and $\mu_1(t)$ is the Kuhn-Tucker multiplier associated with the non-negativity constraint on $x_1(t)$. Then the following must hold at equilibrium:

$$\begin{aligned} -\frac{\partial}{\partial u_1} H_1(t) &= \beta_1^t [D(U(t)) + D'(U(t))u_1(t)] + \lambda_1(t+1) \\ t &= 0, \dots, T-1 \end{aligned} \quad (14)$$

$$\begin{aligned} -\frac{\partial}{\partial u_1} H_1(t)u_1(t) &= 0, \quad u_1(t) \geq 0, \quad -\frac{\partial}{\partial u_1} H_1(t) \geq 0 \\ t &= 0, \dots, T-1 \end{aligned} \quad (15)$$

$$\begin{aligned} -\frac{\partial}{\partial q_1} H_1(t) &= \beta_1^t [c'_1(q_1(t))] + \lambda_1(t+1) \\ t &= 0, \dots, T-1 \end{aligned} \quad (16)$$

$$\begin{aligned} -\frac{\partial}{\partial q_1} H_1(t)q_1(t) &= 0, \quad q_1(t) \geq 0, \quad -\frac{\partial}{\partial q_1} H_1(t) \geq 0 \\ t &= 0, \dots, T-1 \end{aligned} \quad (17)$$

with

$$\begin{aligned} \lambda_1(t) &= \frac{\partial}{\partial x_1} H_1(\lambda_1(t+1), \mu_1(t), x_1(t), u_1(t), q_1(t)) = \lambda_1(t+1) + \mu_1(t) \\ t &= 0, \dots, T-1 \end{aligned} \quad (18)$$

$$\lambda_1(T) = \beta_1^T \pi_1 \quad (19)$$

$$\begin{aligned} \mu_1(t)x_1(t) &= 0, \quad x_1(t) \geq 0, \quad \mu_1(t) \geq 0 \\ t &= 0, \dots, T-1 \end{aligned} \quad (20)$$

Player 2: Similarly we define the Hamiltonian

$$\begin{aligned} H_2(\lambda_2(t+1), x_2(t), u_2(t), q_2(t)) &= \beta_2^t [p(t)u_2(t) - c_2(q_2(t))] + \\ & \lambda_2(t+1)(x_2(t) - u_2(t) + q_2(t)) + \\ & \mu_2(t)x_2(t) \end{aligned} \quad (21)$$

and the following conditions must hold

$$-\frac{\partial}{\partial u_2} H_2(t) = \beta_2^t [D(U(t)) + D'(U(t))u_2(t)] + \lambda_2(t+1) \quad (22)$$

$$-\frac{\partial}{\partial u_2} H_2(t)u_2(t) = 0, \quad u_2(t) \geq 0, \quad -\frac{\partial}{\partial u_2} H_2(t) \geq 0 \quad (23)$$

$$-\frac{\partial}{\partial q_2} H_2(t) = \beta_2^t [c'_2(q_2(t))] + \lambda_2(t+1) \quad (24)$$

$$\begin{aligned}
& t = 0, \dots, T-1 \\
-\frac{\partial}{\partial q_2} H_1(t) q_2(t) &= 0, \quad q_2(t) \geq 0, \quad -\frac{\partial}{\partial q_2} H_2(t) \geq 0 \\
& t = 0, \dots, T-1
\end{aligned} \tag{25}$$

with

$$\begin{aligned}
\lambda_2(t) &= \frac{\partial}{\partial x_2} H_1(\lambda_2(t+1), \mu_2(t), x_2(t), u_2(t), q_2(t)) = \lambda_2(t+1) + \mu_2(t) \\
& t = 0, \dots, T-1
\end{aligned} \tag{26}$$

$$\lambda_1(T) = \beta_2^T \pi_2 \tag{27}$$

$$\begin{aligned}
\mu_2(t) x_2(t) &= 0, \quad x_2(t) \geq 0, \quad \mu_2(t) \geq 0 \\
& t = 0, \dots, T-1
\end{aligned} \tag{28}$$

4 Calibration of the model

To calibrate the different functions appearing in the model, we use simulation results of a CGE model, GEMINI-E3[7][8][9], and a partial equilibrium model of the world energy system[15]. Specifically, we simulated each of these models across a wide range of carbon limits.

GEMINI-E3 is a multi-country, multi-sector, time-stepped General Equilibrium Model incorporating a highly detailed representation of indirect taxation (Bernard and Vielle, 2000). For some purposes, namely the assessment of energy policies directly involving the electric sector, like e.g., the implementation of nuclear programs, the model can incorporate a technological sub-model of power generation better suited for comparing investments in different types of plants. We use the third version of the model that has been especially designed to calculate the social marginal abatement costs (MAC), i. e. the welfare loss of a unit increase in pollution abatement. Beside a comprehensive description of indirect taxation (mainly for France), the specificity of the model is to simulate all relevant markets: markets for commodities (through relative prices), for labor (through wages), for domestic and international savings (through rates of interest and exchange rates). Terms of trade (i.e. transfers of real income between countries resulting from variations of relative prices of imports and exports), and then “real” exchange rates, can then be precisely measured¹².

POLES is a global partial equilibrium model of the world energy system with 30 regions. POLES produces detailed world energy and CO2 emissions projections by region through the year 2030. POLES combines some features of “top-down” models in that prices play a key role in the adjustment of most variables in the model but retains detail in the treatment of technologies characteristic of “bottom-up” models. The dynamics of the model is given by a recursive simulation process that simulates energy demand, supply and prices adjustments[15]. Marginal abatement cost curves for CO2 emissions reductions are assessed by the introduction of a carbon tax in all areas of fossil fuel energy use. This carbon tax leads to adjustments in the final energy demand within the model, through technological changes or implicit behavioral changes, and through replacements in energy conversion systems for which the technologies are explicitly defined in the model. The POLES’ model has been already used to analyze economic impacts of climate change policies and the consequences of implementing flexibility mechanisms[10][16][17][18].

The basic data used to calibrate the model are:

¹²The real exchange rate between two countries is the relative price of the “numéraires” chosen in each country (and usually based on a basket of goods representative of GDP). It is not identical to the monetary exchange rate of the currencies of the two countries: in particular, the real exchange rate can evolve between countries belonging to a same monetary union.

- the *demand for flexible instruments* by non Annex B countries (other than Russia & Ukraine, and including or not the U.S. according to the case); i. e. what these countries are globally willing to purchase at a given price (or, symmetrically, what they are willing to pay for a given amount of flexible instruments, either emissions permits from Russia or CDM from China);
- the *marginal abatement costs curves* in Russia & China, as a function of emissions in the reference case, the magnitude of the substitutions and demand elasticities, and adjustment dynamics[46];
- the *amount of hot air* in Russia & Ukraine, as a function of emissions trajectories in the Business-As-Usual scenario in Russia & the Ukraine, and emissions target in the Kyoto Protocol and in the next commitment periods.

4.1 Law of demand

Figure 1 represents the demand curves for flexible instruments from 2010 to 2040 computed with GEMINI-E3. It is assumed that the U.S. does not participate in the Kyoto Protocol, and does not implement domestic climate change policies.

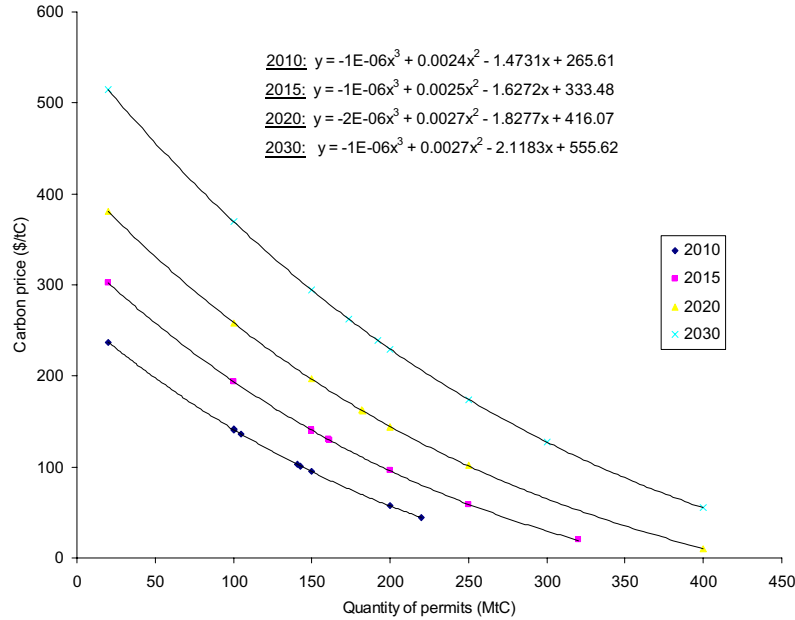


Figure 1: Law of demand from GEMINI-E3

4.2 Abatement costs in Russia and China

Marginal abatement costs (MAC) curves are derived by setting progressively tighter abatement levels and recording the resulting shadow price of carbon or by introducing progressively higher carbon taxes and recording the quantity of abated emissions¹³.

MAC curves for Russia are taken from GEMINI-E3 whereas MAC curves for China are from the POLES model. Even if the two models belong to different paradigms, it has been shown

¹³As explained by Ellerman and Decaux[22], a computable general equilibrium (CGE) model can produce a “shadow price” for any constraint on carbon emissions for a given region R at time T. A MAC curve plots the shadow prices corresponding to different level of emissions reduction. MAC curves are upward-sloping curve: the shadow price of emissions reduction rise as an increasing function of emissions reduction.

that MAC curves from the two models are comparable[44]. This result is true if we take MAC curves representing only the “primary costs” of the carbon policy. It is justified to use these curves if we assume that an industry-level emissions permits system is implemented rather than a government-level emissions permits system since private entities do not take into account the social cost but the private costs of their abatement decisions[4]. Welfare costs of climate policies will thus not be reported.

In order to measure the welfare impact of international emissions trading in a second-best world, one might not take into account only the primary costs of the carbon policy (direct tax burden) but also the “secondary costs” due to pre-existing distortions.¹⁴

The results of our simulations are compiled in table 1. Figures 2 and 3 show MAC curves for Russia & Ukraine and China. They have been plotted as a function of the amount of carbon emissions reduction below reference emissions. We can see that the potential for low cost abatement are much higher in China than in Russia. At 10\$/tC, the amount of emissions reductions is closed to 40MtC in Russia and closed to 230MtC in China.

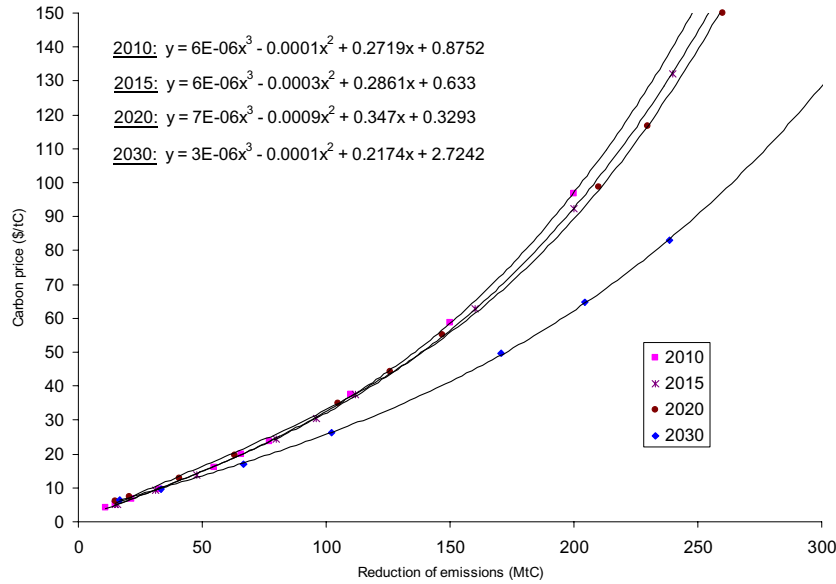


Figure 2: MAC curves of Russia from GEMINI-E3, 2010-2030

¹⁴In a second best setting, the gross efficiency cost of various environmental policies comprise the primary costs and the cost impact of pre-existing taxes, including the “tax-interaction effect” and the “revenue recycling effect”. According to Goulder *et al.*[26], the tax-interaction effect as two components: the policy instrument increase the price of goods, implying an increase in the cost of consumption and thus a reduction in the real wage. This reduce labor supply and produces a marginal efficiency loss which equals the tax wedge between the gross and net wage multiplied by the reduction in labor supply. In addition, the reduction in labor supply contributes to a reduction in tax revenues. The revenue recycling effect corresponds to the efficiency gain from the reduction in the rate of pre-existing distortionary tax obtained with the revenues raised from the emissions tax[25]. Usually, pre-existing distortionary taxes raises the costs of a given tax since the tax interaction effect dominates the revenue-recycling effect.

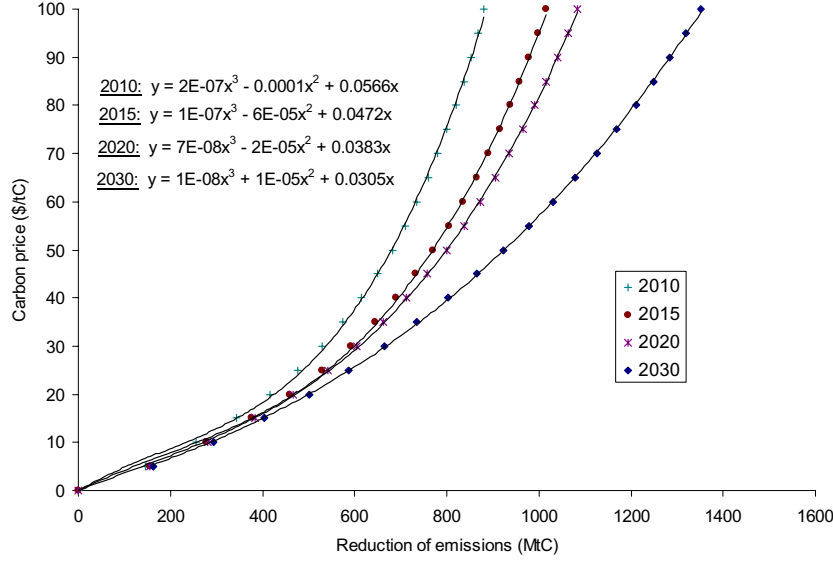


Figure 3: MAC curves of China from POLES, 2010-2030

4.3 Russian hot air

MAC curves in Russia do not include the amount of hot air available in the 2010-2030 period. The size of the Russian hot air is far from being certainly established as it largely depends on GDP forecasts. The amount of hot air (in 2010) estimated by the economic models range from 150 to 500 MtC[41]. In the new International Energy Outlook[20], the U.S. Department of Energy projects annual energy-related carbon emissions in the Former Soviet Union to rise from approximately 1036 MtC in 1990 to 745 MtC in 2010 and 884 MtC in 2020 in the baseline scenario. According to the DOE, and if we assume the terms of the “Kyoto Forever” scenario, the hot air might be equal to 291 MtC in 2010 and 152 MtC in 2020. In the EPPA model, the hot air is projected to decline from 186.5 MtC in 2010 to 105 MtC in 2015, and 41 MtC in 2020 whereas it goes from 300 MtC in 2010 to 136 MtC in 2030 in GEMINI-E3[9]. Our study will be based on the EPPA estimates about the Russian hot air.

5 Results

5.1 Scenarios

Two scenarios are constructed to investigate the impact of strategic behaviors on the markets for tradable permits:

- **Monopoly:** Being the only supplier in the market, Russia acts as a monopoly.
- **Duopoly:** Russia and China play the emissions permits game described in section 3.

In the two cases, the demand of emissions permits is assessed under a “Kyoto Forever” scenario, implying that Annex B countries are committed to a constant level of emissions over time - the one set in the Protocol - while non-Annex B countries remain free of any commitment. We suppose that emissions permits are freely tradable in the international market (no “concrete

ceilings”¹⁵ on emissions trading). It is also assumed that Russia can freely trade its hot air, and that emissions permits can be banked without constraint. The terminal value of the stock of permits is supposed to be equal to zero. We apply a 5% discount rate. Finally, we assume no transaction costs in the reference cases. The impacts of China’s participation in the next commitment periods and transaction costs will on the emissions markets will be assessed further.

	2010	2015	2020	2030
	Supply (in MtC)			
Duopoly-Russia	76.27	93.85	113.91	143.78
Duopoly-China	82.93	100.87	121.69	153.77
Monopoly-Russia	109.46	135.38	168.33	229.37
	Abatement (in MtC)			
Duopoly-Russia	40.04	43.03	42.23	48.49
Duopoly-China	83.00	103.16	123.82	149.28
Monopoly-Russia	88.77	93.66	93.76	112.36
	Banking of permits (in MtC)			
Duopoly-Russia	149.78	203.96	173.29	0.00
Duopoly-China	0.07	2.36	4.49	0.00
Monopoly-Russia	165.31	228.59	195.02	0.00
	Price of permits (in \$/tC)			
Duopoly	89.86	108.58	123.86	128.37
Monopoly	137.96	166.00	192.48	213.22

Table 1: Simulation results for the two scenarios

Figure 4 reports the supply of permits in the two reference case. In the monopoly scenario, emissions permits sold by Russia go from 110 MtC in 2010 to 230 MtC in 2030. The size of the emissions market increases dramatically when China is allowed to enter the market. The total supply of emissions permits ranges from 160 MtC in 2010 to 300 MtC in 2030. Russia’s exports of emissions permits are reduced by more than 30% in the duopoly case compared to the situation where it has a monopolistic behavior. China and Russia sell more or less the same amount of permits at the Cournot-Nash equilibrium.

Figure 5 shows that Russia’s emissions reduction are rather stable over time in the monopoly case. In this policy scenario, the share of emissions reductions in total supply decrease from 80% in 2010 to 50% in 2030. Real reductions of emissions are reduced by more than 50% in Russia when China participate in the emissions markets. Having no hot air, China has to reduce its emissions in order to sell emissions permits. In the duopoly case, China is the main exporter of permits. China’s real emissions reductions are twice higher than Russia’s one in 2010. They become three times higher in 2030.

As shown in figure 6, Russia banks a large portion of hot air (88% in 2010) in the monopoly case in order to maximize its trading gains. As expected, the amount of permits banked by Russia decreases when it has to compete with China in the international markets for emissions

¹⁵“Concrete ceilings” is a rule that has been proposed by the European Union to guarantee a minimum emissions reduction percentage in Annex B regions. This proposal echoes the “supplementarity” criterion (article 6.1(d) of the Kyoto protocol saying that “the acquisition of emissions reduction units shall be supplemental to domestic actions for the purpose of meeting commitments under article 3”. On the economic impacts of concrete ceilings, see [16].

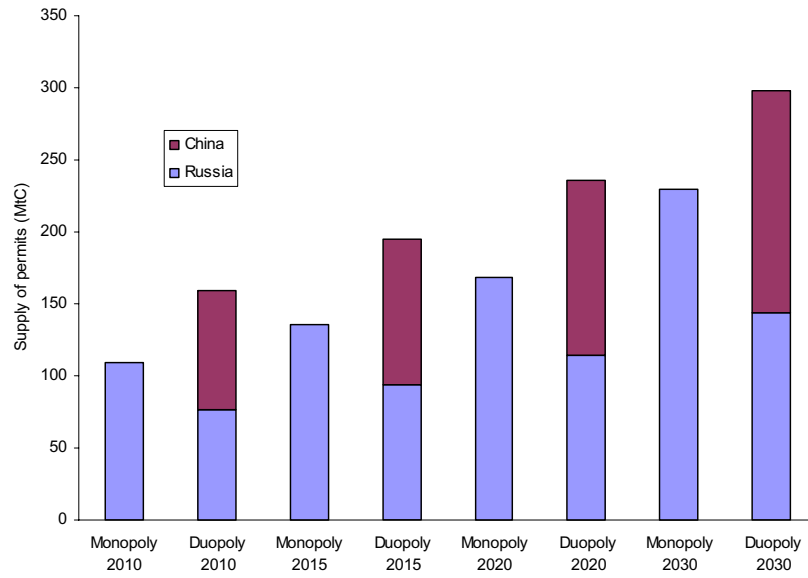


Figure 4: supply of permits (Monopoly & Duopoly cases)

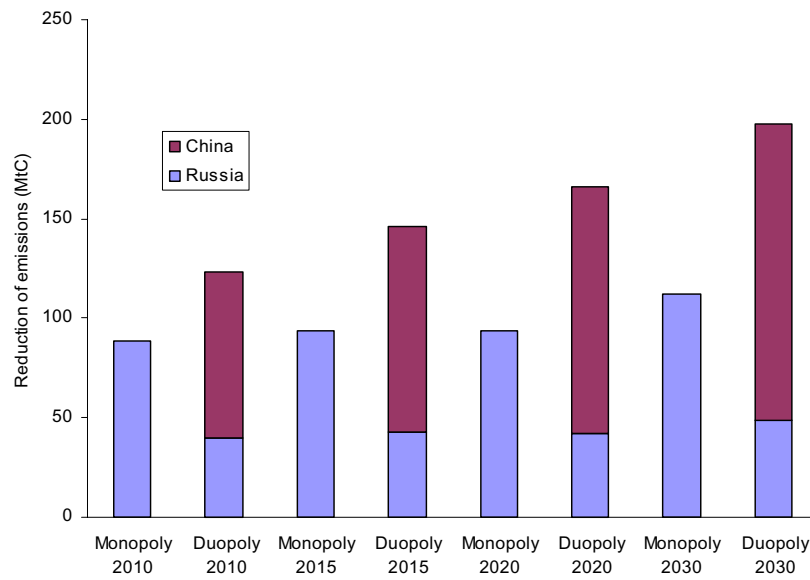


Figure 5: Reduction of emissions (Monopoly & Duopoly cases)

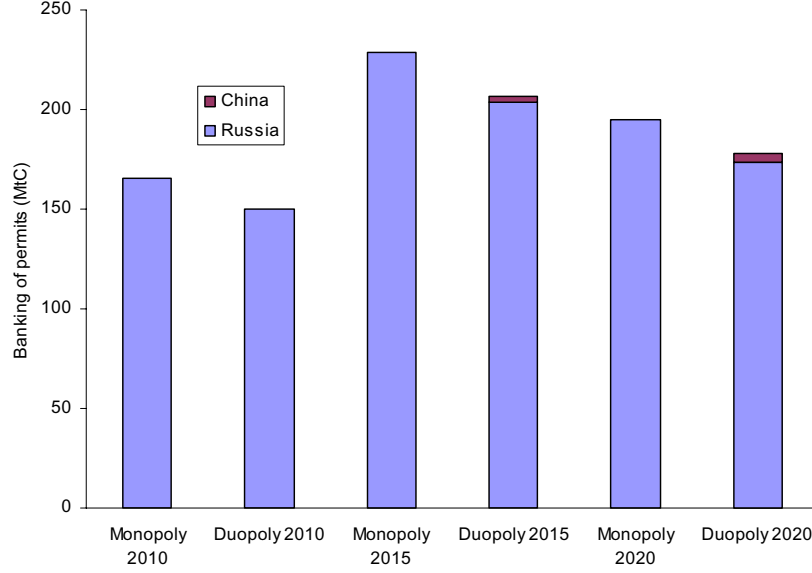


Figure 6: Banking of permits (Monopoly & Duopoly cases)

permits. However, the reduction of permit's banking is rather low. Consequently, the reduction of Russia's sales in the duopoly case does not come from a reduction of banked permits but rather from abatement. China has a low incentive to bank emissions permits since the increase of permit price over time is limited (compared to the 5% discount rate).

As said before, some authors have argued that the permit price might be close to zero in 2010 due to the U.S. withdrawal from the Kyoto Protocol. In other works [3][12][11], the permit price might range from 20\$/tC to 60\$/tC in 2010 if we assume a myopic monopolistic behavior of Russia. Bernard et al.[9] have shown that prices might be even higher in the near term if we suppose a forward looking (inter-temporal optimization) monopolistic behavior of Russia.

Our study is consistent with previous findings. Since the permits demand is relatively inelastic to prices in GEMINI-E3, there is a rather high incentive for Russia to act as a monopolist, and to let prices go up by restricting its supply of permits. In the monopoly case, the permit price rises from 140\$/tC in 2010 to 213\$/tC in 2030 (figure 7). When revenues from permits sales depend on its own supply and the other country's supply (duopoly scenario), the Nash-Cournot equilibrium price is much lower than the monopoly price. Set at 90\$/tC in 2010, the permit price rise slowly to 128\$/tC in 2030.

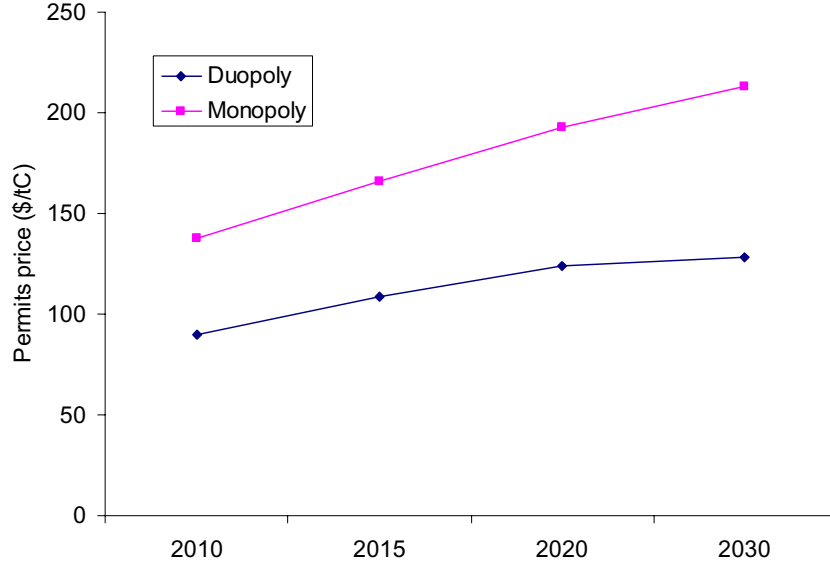


Figure 7: Price of permits (Monopoly & Duopoly cases)

6 Sensitivity analysis: transaction costs and participation of China

In this section, we assess the sensitivity of our modelling results to parameters of the model. The two parameters on which there is a great uncertainty, and which are likely to have an impact on the price of emissions permits are:

- The level of participation of China in the international effort to curb GHG emissions.
- The transaction costs associated with CDM projects.

6.1 Transaction costs

U.S. experience with emissions trading shows that transaction costs might reduce the cost-effectiveness of the instrument. For example, transaction costs in the Emission Trading Program (ETP) market¹⁶ have been substantial, due to both their bilateral nature and to the difficulty in quantifying eligible emissions reductions[21]. By contrast, the SO₂ allowance trading system established by the Clean Air Amendments of 1990 was explicitly designed to minimize transaction costs¹⁷. Current experiences in the pilot phase of Joint Implementation¹⁸ show that transaction costs can seriously erode the cost saving potential of JI-type projects[21]. Regarding transaction costs associated with CDM projects, there is little empirical evidence[38][32]. Baseline determination can be a source of high uncertainty and transaction costs in identifying GHG emissions reductions in cooperative implementation projects. Moreover, the absence of clear ground rules

¹⁶The Emission Trading Program (ETP) has been established by the US EPA under the 1977 Clean Air Act as part of the New Source Review (NSR) process of permitting new air pollution sources in non attainment regions.

¹⁷The U.S. experience with sulfur dioxide allowance trading shows that transaction costs can be made smaller when the government involvement in an allowance transaction simply involves recordation, not case-by-case review or approval, and the source has numerous venues in which to transact allowances[37][31].

¹⁸Joint implementation allows any party operating under FCCC Article 4(2)(a) to undertake its GHG abatement activities 5 wherever conditions and partners are most welcoming.

and guidelines for baseline assessment can inhibit private-sector participation in CDM and prevent developing countries from playing a lead role in the project identification and development process.

Introducing transaction costs in modelling exercises is not obvious. There are different ways to proceed. One can use a *price approach* that consists in adding an extra cost (or fee) per ton of emissions reduction [32]. One might opt for a *quantity approach*: scaled back economy-wide estimates of emissions reductions realized at a given level of carbon tax to take account of the fact that only a very limited subset of possible emissions reduction options would be feasible as projects, and eligible for crediting under CDM rules. Another solution might be to exclude some sectors from the CDM mechanisms and to limit CDM potential to some sectors where transaction costs would be lower, let's say energy-intensive industries and the energy sector (*Sectoral approach*). Finally, we could limit CDM projects to technologies that could be easily transfers in DCs (*Technology approach*).

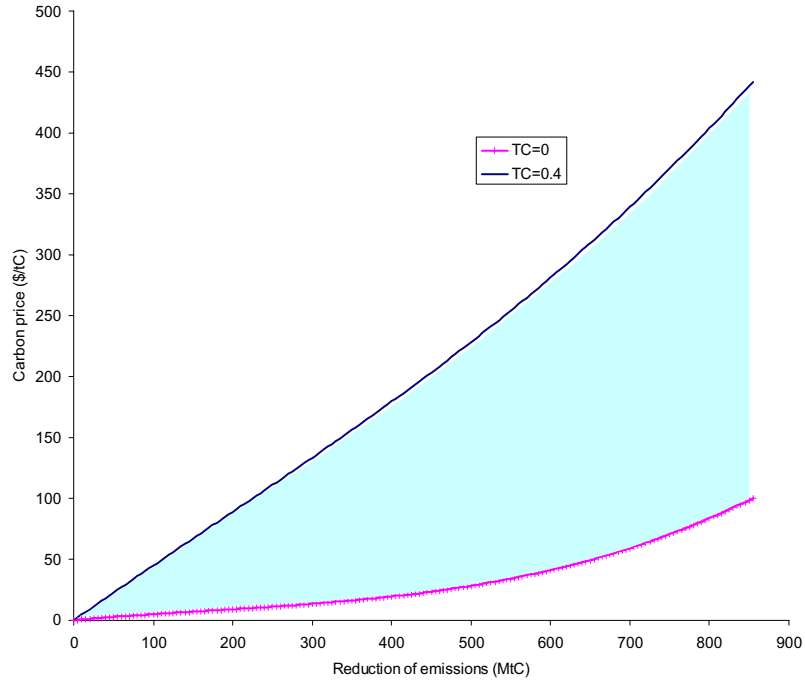


Figure 8: CDM potential in China, 2010

In this study, we use the *price approach*. Transaction costs are introduced directly in the MAC curve by applying a fee to CDM projects in China. In our simulations, the fee ranges from 0 to 40\$ per ton of carbon emissions reduction. As shown in Figure 8, when we assume no transaction costs, the potential for CDM in China in 2010 is 100MtC at 4.86\$/tC. When transaction costs are 40\$/tC, the potential for CDM is 100MtC at 44.86\$/tC in 2010.

6.2 Participation of China

In the reference scenario, it is assumed that China does not participate in GHG emissions mitigation. However, one might expect some DCs, including China, to participate in next commitment periods. Various approaches have been proposed to differentiate GHG emissions reductions worldwide. One of the candidate for allocating emissions reduction across countries in next commitment periods is the “Soft-Landing” approach [10]; it consists in 1) stabilizing world carbon emissions at 10 GtC by 2030, 2) applying Kyoto forever for Annex B regions,

and 3) reducing linearly emissions growth rates for DCs at different time horizons, taking into account per capita GDP, per capita carbon emissions, and population growth.

Under this long run policy case, China would have to stabilize carbon emissions by 2030. According to the POLES models, China's baseline emissions are 2.4 Gt in 2030 and the emissions reduction required to stabilize China's emissions in 2030 is 274 MtC [10].

In this study, we use the Soft Landing scenario computed in POLES as the upper bound. As shown in figure 9 and 10, China's emissions reductions range from 0 to 300 MtC in our simulations.

6.3 Simulation results

Figures 9 and 10 summarize the supply of emissions permits from China in 2010 and 2030 for the different simulations. As shown in the graphs, the sales from China are highly sensitive to transaction costs but not as much as domestic emissions reductions. As long as transaction costs stay relatively low, China might accept emissions targets in the next commitment periods without affecting its permits sales. China sell 83 MtC in 2010 in the no transaction cost and no commitment scenario (Reference case). China's supply might be reduced by 40% in 2010 and 73% in 2030 when we assume high transaction costs (40\$/tC) and a commitment to stabilize emissions in 2030. The amount of permits sold by China would be only reduced by 14 MtC in 2010 and 18 MtC in 2030 if we take an average scenario with 20 dollars of transaction costs per ton of emissions reduction and a 150 MtC commitment in 2030.

	Russia					China				
	40	30	20	10	0	40	30	20	10	0
2010										
300	81.2	80.7	80.0	78.8	76.9	51.3	57.6	64.6	72.4	81.3
200	79.5	79.3	78.9	78.0	76.7	56.1	61.5	67.5	74.2	81.9
100	77.9	77.9	77.8	77.3	76.5	60.8	65.4	70.4	76.0	82.4
0	76.3	76.5	76.7	76.6	76.3	65.6	69.2	73.3	77.8	82.9
2015										
300	99.0	98.6	97.8	96.5	94.6	67.6	74.2	81.5	89.8	99.2
200	97.3	97.1	96.6	95.7	94.3	72.6	78.3	84.6	91.7	99.8
100	95.6	95.6	95.4	95.0	94.1	77.6	82.4	87.6	93.6	100.3
0	93.9	94.1	94.3	94.2	93.9	82.6	86.5	90.7	95.5	100.9
2020										
300	120.7	120.0	118.8	117.1	114.7	85.8	92.9	100.8	109.7	119.9
200	118.7	118.2	117.5	116.3	114.4	91.3	97.4	104.1	111.8	120.5
100	116.6	116.5	116.1	115.4	114.2	96.7	101.8	107.5	113.8	121.1
0	114.6	114.8	114.8	114.5	113.9	102.1	106.2	110.8	115.9	121.7
2030										
300	157.1	155.2	152.6	149.3	145.0	112.4	120.4	129.5	139.8	151.6
200	154.0	152.5	150.6	148.0	144.6	118.8	125.7	133.5	142.2	152.3
100	150.8	149.9	148.5	146.7	144.2	125.2	131.0	137.4	144.7	153.0
0	147.7	147.2	146.5	145.4	143.8	131.7	136.2	141.4	147.2	153.8

Table 2: Supply of permits, in MtC

Figures 11 and 12 show that transaction costs and the participation of China in emissions reductions might have a significant impact on the price of emissions permits. In 2010, the permit price may increase from 90\$/tC in the reference case to 116\$/tC with high transaction costs

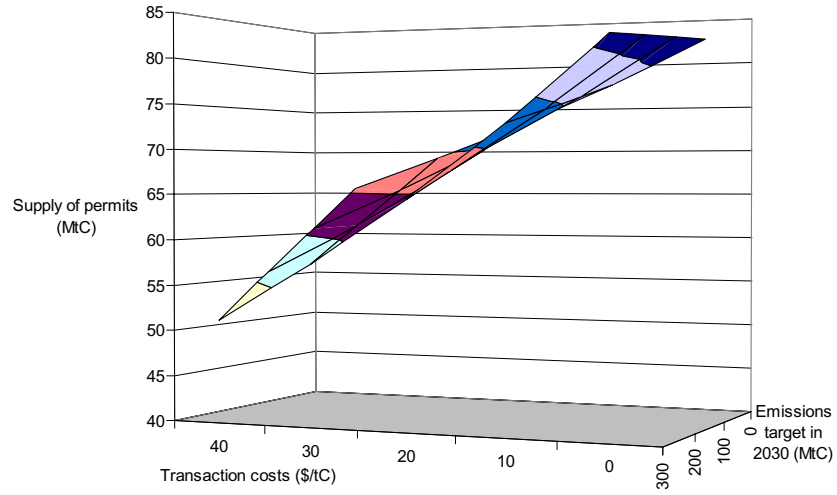


Figure 9: China's supply response to transaction costs and China's participation in 2010

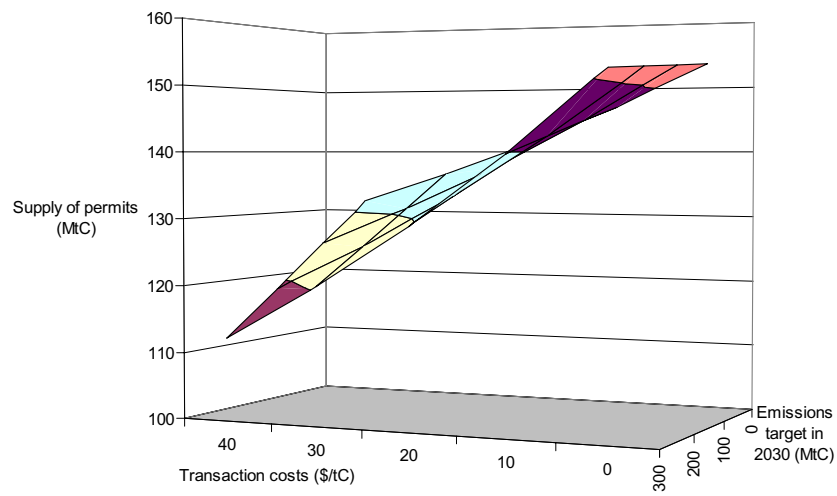


Figure 10: China's supply response to transaction costs and China's participation in 2030

and a stabilization of China's emissions in 2030. In 2030, the permit price rise from 128\$/tC to 163\$/tC.

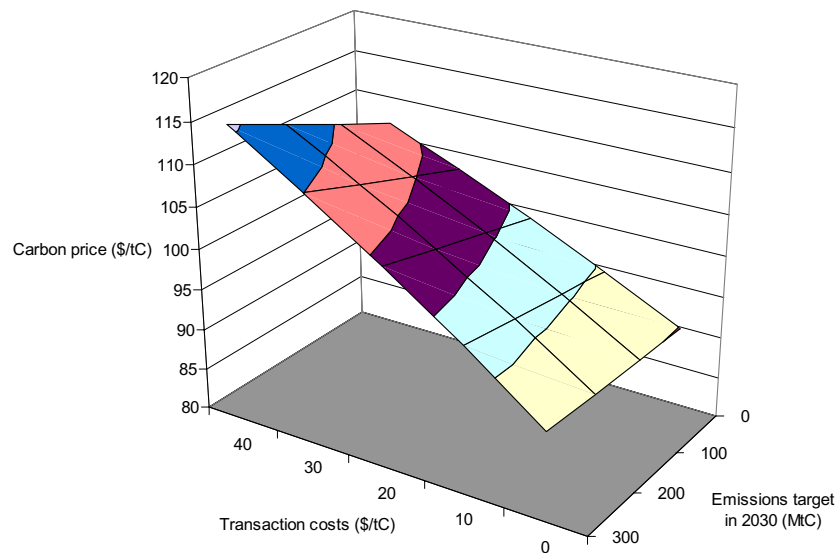


Figure 11: Price response to transaction costs and participation of China in 2010

Table 1 depicts total revenue from permits trading for Russia and China in 2010 and 2030 with different parameter's values. Total revenues would be around US\$ 3.4 billion for Russia and US\$ 3.7 billion for China over the first commitment period if we assume zero transaction costs associated with CDM projects and no reduction targets for China in the next commitment periods. Trading gains are sensitive to parameter's values in the short run. China's revenues are reduced in the presence of transaction costs and with a 300 MtC commitment in 2030 whereas it is gainful for Russia. One can note that the negative impact of transaction costs and commitments is very limited in 2030 for China.

China's revenues from permits selling are not really sensitive to parameter's values in the long run. Trading gains range from US\$ 9.1 billion to US\$ 9.9 billion in 2030 depending on transaction costs and the level of China's commitment. By contrast, Russia's revenues are relatively sensitive to the value of the parameters. Trading gains are likely to increase by 39% compared to the reference case when China is committed to stabilize its emissions by 2030 and when transaction costs are 40\$/tC.

	Russia				China			
	2010		2030		2010		2030	
	0\$/tC	40\$/tC	0\$/tC	40\$/tC	0\$/tC	40\$/tC	0\$/tC	40\$/tC
0 MtC	3.43	4.07	9.23	11.15	3.73	3.50	9.87	9.94
100 MtC	3.45	4.27	9.28	11.70	3.71	3.34	9.85	9.71
200 MtC	3.47	4.48	9.34	12.26	3.70	3.16	9.84	9.46
300 MtC	3.49	4.69	9.39	12.83	3.69	2.97	9.82	9.17

Table 3: Revenue from permit sales, in US\$ billion

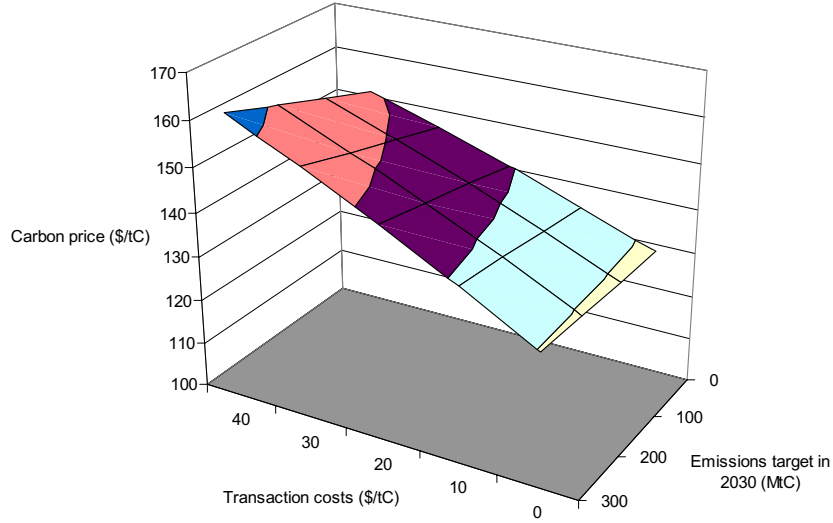


Figure 12: Price response to transaction costs and participation of China in 2030

7 Concluding remarks

In this paper, we have presented a computable two-level dynamic game of tradable permits for carbon emissions between Russia, China, and Annex B Countries. This model was calibrated with GEMINI-E3, a multi-country, multi-sector, dynamical-recursive computable general equilibrium model developed to analyze climate change policies, and POLES, a global partial equilibrium model of the world energy system with 30 regions.

In our simulations, it appears that the competition between Russia and China on the international markets for carbon emissions permits should lower significantly the permit prices. The introduction of transaction costs in China and the stabilization of China emissions by 2030 do not modify significantly the revenue of that country in emissions trading. This simulation results tend to show that the participation of DCs in an international emissions trading scheme with reasonable abatement targets for them could be beneficial to both Annex B countries and DCs.

Indeed, a high level of uncertainty remains in several parameters of the model; in particular the amount of hot air, MAC curves, emissions targets for Annex B countries in the next commitment periods, etc. The next step in this research will be the implementation of a stochastic equilibrium model in the line of Refs. [29] and [30]

References

- [1] BABIKER M.H., REILLY J.M., MAYER M., ECKAUS R.S., SUE WING I., AND HYMAN R.C., “The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Revisions, Sensitivities, and Comparisons of Results”, MIT Joint Program on the Science and Policy of Global Change, report 71, Cambridge, MA, USA, 2000.
- [2] BABIKER M., VIGUIER L., ELLERMAN D., REILLY J., AND CRIQUI P., “Welfare impacts of hybrid climate policies in the European Union”, Report no 74, MIT Joint Program on the Science and Policy of Global Change, Cambridge, MA, June 2001.

- [3] BABIKER M., JACOBY H., REILLY J., AND REINER D., "The Evolution of a Climate Regime: Kyoto to Marrakech", Report no 82, MIT Joint Program on the Science and Policy of Global Change, Cambridge, MA, February 2002.
- [4] BABIKER M., REILLY J., VIGUIER L., Is International Trading Always Beneficial?, mimeo, August 2002.
- [5] BAŞAR T. AND OLSDER G.J., *Dynamic Noncooperative Game Theory*, Academic Press, London, 1989.
- [6] BENCHEKROUN H., LONG N.V., "Leader and Follower: A Differential Game Model", working paper, CIRANO, Montreal, February 2001.
- [7] BERNARD A., VIELLE M., "Toward a Future for the Kyoto Protocol: Some Simulations with GEMINI-E3", unpublished paper, 2001.
- [8] BERNARD A., VIELLE M., "Does Non Ratification of the Kyoto Protocol by the US Increase the Likelihood of Monopolistic Behavior by Russia in the Market of Tradable Permits?", paper presented at the 5th Annual Conference on Global Economic Analysis, GTAP, Taipei 2002.
- [9] BERNARD A., REILLY J., VIELLE M., AND VIGUIER L., "Russia's role in the Kyoto Protocol", paper presented at the Annual Meeting of the International Energy Workshop jointly organized by EMF/IEA/IIASA, Stanford University, USA, 18-20 June 2002.
- [10] BLANCHARD O., CRIQUI P., KITOUS A., VIGUIER L., "Combining Efficiency with Equity: A Pragmatic Approach" In: Inge Kaul et al. (ed.), *Providing Global Public Goods: Making Globalization Work for All*, United Nations Development Programme, forthcoming 2002.
- [11] BLANCHARD O., CRIQUI P. AND KITOUS A., "Après La Haye, Bonn et Marrakech : le futur marché international des permis de droits d'émissions et la question de l'air chaud, IEPE, working Paper, Janvier 2002.
- [12] BÖHRINGER C., "Climate Politics From Kyoto to Bonn : From Little to Nothing !!?", ZEW Discussion Paper 01-49, 2001.
- [13] COASE R. H., "The nature of the firm", *Economica*, 4, 1937), 386-405.
- [14] COASE R. H., "The Problem of Social Cost", *Journal of Law and Economics*, 3, 1960, 1-44.
- [15] CRIQUI P., POLES 2.2., JOULE II Programme, European Commission DG XVII - Science Research Development, Bruxelles, Belgium, 1996.
- [16] CRIQUI P., MIMA S., VIGUIER L., "Marginal abatement costs of CO2 emission reductions, geographical flexibility and concrete ceilings: an assessment using the POLES model", *Energy Policy*, 27, 1999, 585-601.
- [17] CRIQUI P., VIGUIER L., Trading Rules for CO2 Emission Permits Systems: a Proposal for Ceilings on Quantities and Prices, Working Paper 18, IEPE, Grenoble, France, 2000.
- [18] CRIQUI P., VIGUIER L., "Kyoto and Technology at World Level: Costs of CO2 Reduction under Flexibility Mechanisms and Technical Progress", *International Journal of Global Energy Issues*, 14, 2000, 155-168.
- [19] DOCKNER E.J., JORGENSEN S., LONG N.V., AND SORGER G., *Differential Games in Economics and Management Sciences*, Cambridge University Press, Cambridge, UK.

- [20] DOE, *International Energy Outlook (IEO 2002)*. Energy Information Administration, Washington, DC, 2002.
- [21] DUDEK D.J., WIENER J.B., Joint Implementation, Transaction Costs, and Climate Change, OCDE, OCDE/GD(96)173, Paris, 1996.
- [22] ELLERMAN A.D., AND DECAUX A., "Analysis of Post-Kyoto CO₂ Emissions Trading Using Marginal Abatement Curves, MIT Joint Program on the Science and Policy of Global Change, Report no 40, Cambridge, MA, 1998.
- [23] FERRIS M.C., PANG J.S., *Complementarity and Variational Problems: State of the Art*, SIAM Publications, Philadelphia, Pennsylvania, 1997.
- [24] FERRIS M.C., MUNSON T.S., "Complementarity problems in GAMS and the PATH solver", *Journal of Economic Dynamics and Control*, 24, 2000, 165-188.
- [25] GOULDER, L.H., "Effects of Carbon Taxes in an Economy with prior Tax Distortions: An Intertemporal General Equilibrium Analysis", *Journal of Environmental economics and Management*, 29, 1995, 271-97.
- [26] GOULDER, L.H., PARRY, I.W.H., WILLIAMS III, R.C., BURTRAW, D., The Cost-Effectiveness of Alternative Instruments for Environmental Protection in a Second-Best Setting, NBER Working Paper 6464, Cambridge, Mass., March 1998.
- [27] HAHN R.W., HESTER G.L., "Marketable Permits: Lessons for Theory and Practice", *Ecology Law Quarterly*, 16, 1989, 361-406.
- [28] HAMALAINEN R., HAURIE A. AND KAITALA V., "Equilibria and Threats in a Fishery Management Game", *Optimal Control Applications and Methods*, Vol. 6, no 4, 315-333, 1986.
- [29] HAURIE A. AND MORESINO F., "S-Adapted Oligopoly equilibria and Approximations in Stochastic Variational Inequalities", *Annals of Operations Research*, to appear.
- [30] HAURIE A., SMEERS Y., AND ZACCOUR G., "Stochastic Equilibrium Programming for Dynamic Oligopolistic Markets", *Journal of Optimization Theory and applications*, 66, 2, August 1990.
- [31] JOSKOW P.L., SCHMALENSEE R., BAILEY E.M., "The Market for Sulfur Dioxide Emissions", *The American Economic Review*, 88, 4, 1998, 669-685.
- [32] JOTZO F., MICHAELOWA A., "Estimating the CDM market under the Marrakech Accords", *Energy Policy*, article in press.
- [33] KAITALA V., "Game Theory Models of Fisheries Management-A Survey" in T. Basar (ed.), *Dynamic games and applications in economics*, Springer, New York, 1986, 252-66.
- [34] LÖSCHEL A., AND ZHANG Z.X., "The Economic and Environmental Implications of the US Repudiation of the Kyoto Protocol and the Subsequent Deals in Bonn and Marrakech", Nota Di Lavoro 23.2002, Fondazione Enie Enrico Mattei, April 2002.
- [35] MÄLER K.-G., AND DE ZEEUW A.J., "The Acid Rain Differential Game", *Environmental and Resource Economics*, 12, 1998, 167-184.
- [36] MANNE A.S., MENDELSON R., RICHEL R., "MERGE - A Model for Evaluating Regional and Global Effects of GHG Reduction Policies", *Energy Policy*, 23, 1, 1995, 17-34.

- [37] MCLEAN B.J., "Evolution of Marketable Permits: The U.S. Experience With Sulfur Dioxide Allowance Trading", *International Journal of Environmental and Pollution*, 8, 1/2, 1997, 19-36.
- [38] MICHAELOWA, A., STRONZIK, M., Transaction Costs of the Kyoto Mechanisms, HWWA Discussion Paper 175, Hamburg, 2002.
- [39] DE MOOR, A.P.G., BERK M.M., DEN ELZEN M.G.J., AND VAN VUUREN D.P., "Evaluating the Bush Climate Change Initiative", RIVM Report 728001019/2002, 2002.
- [40] NAGURNEY A. AND KANWALROOP K.D. "Marketable pollution permits in oligopolistic markets with transaction costs", *Operations Research*, Vol. 48, No. 3, pp. 424-435, 2000.
- [41] PALTSEV, S. V., The Kyoto Protocol: "Hot air" for Russia?, Department of Economics, University of Colorado, Working Paper No. 00-9, October 2000.
- [42] ROSEN J. B., *Existence and uniqueness of equilibrium points for concave N-person games*, *Econometrica*, 33 (1965), pp. 520-534.
- [43] STAVINS R.N., "Transaction Costs and Tradeable Permits", *Journal of Environmental Economics and Management*, 29, 1995, 133-148.
- [44] VIELLE M., "Comparaison de deux valuations", Document VI in "Effet de serre : modulation conomique et dcision publique" Rapport du groupe prsid par P-N Giraud, Commissariat Gnral du Plan, Documentation Franaise, Mars 2002.
- [45] VIGUIER L., "The U.S. Climate Change Policy: A Preliminary Evaluation", Policy Brief, French Center on the United States at the Institut Français des Relations Internationales (CFE-IFRI), March 2002.
- [46] WEYANT, J.P., HILL J.N., "Introduction and overview" , *The Energy Journal*, Special Issue J.P. Weyant (eds.), "The Costs of the Kyoto Protocol: A Multi-Model Evaluation", 1999, vii-xliv.
- [47] DE ZEEUW A.J., VAN DER PLOEG F., "Difference Games and Policy Evaluation: A Conceptual Framework", *Oxford Economic Papers*, 43, 1991, 612-636.
- [48] ZHANG, Z.X., "Estimating the Size of the Potential Market for the Kyoto Flexibility Mechanisms", *Weltwirtschaftliches Archiv - Review of World Economics*, 136(3), 491-521.

Appendix. The GAMS code for solving the dynamic game model

```

Sets  J      Players          /j1*j2/
      T      planning period  /1*4/
      T0(T)  initial period
      T1(T)  time period subset
      T2(T)  time period subset
      T3(T)  time period subset
      T4(T)  time period subset
      TT(T)  terminal period ;

Alias (J,K);

*      Marginal cost function:

*       $f'(q) = c * q^3 + \text{beta} * q^2 + d * q + \text{tc} * q$ 

table data(J,*,T)  cost function data
               1      2      3      4
      j1.c      1E-05   5E-06   5E-06   3E-06
      j2.c      2E-07   1E-07   7E-08   1E-08
      j1.beta   -0.0012 -0.0005 -0.0006 -0.0006
      j2.beta   -0.0001 -6E-05  -2E-05  1E-05
      j1.d       0.307   0.2816  0.3053  0.2869
      j2.d       0.0566  0.0472  0.0383  0.0305

*      Demand function:

*       $q(p) = \text{delta} * p + a$ 

table dem(*,T)  linear demand function data
               1      2      3      4
      delta   -1.0339  -1.0334  -0.9803  -0.8035
      a       252.1    306.92   357.02   400.69

table pol(J,*,T)  Domestic emissions targets
               1      2      3      4
      j1.tar   0       0       0       78
      j2.tar   0       0       0       0

parameter      c(J,T),
               l(J,T),
               beta(J,T),
               d(J,T)      domestic emission target,
               pi(J)      terminal value of permits,
               rho(J)     discount rate,
               delta(T),
               a(T),

```

```

tar(J,T)      domestic emissions target ;

c(J,T) = data(J,"c",T); beta(J,T) = data(J,"beta",T); d(J,T) =
data(J,"d",T); delta(T) = dem("delta",T); a(T) = dem("a",T);
tar(J,T) = pol(J,"tar",T);

```

parameter

```

x0(J)  initial stock of permits (e.g. hot air)
        /J1 = 186
        J2 = 0/
x1(J)  additional stock of permits
        /J1 = 105
        J2 = 0/
x2(J)  additional stock of permits
        /J1 = 41
        J2 = 0/
x3(J)  additional stock of permits
        /J1 = 0
        J2 = 0/
rho(J) discount factor
        /J1 = 0.95
        J2 = 0.95/
pi(J)  terminal value of permits
        /J1 = 0
        J2 = 0/
tc(J)  transaction costs
        /J1 = 0
        J2 = 0/

```

positive variables

```

u(J,T)      supply,
q(J,T)      abatement level,
uu(T)       total supply ,
nux(J,T)    x positive multiplier

```

variables

```

p(T)        permit price,
x(J,T)      Permits banking,
lambda(J,T) costate variable,
r(T)        total abatement,
b(T)        total banking;

```

equations

```

posix(J,T),
demand(T),
total_supply(T),
supply(J,T),

```

```

        abatement(J,T),
        state_eq(J,T),
        costate_eq(J,T),
        total_abat(T),
        total_bank(T);

posix(J,T)..          x(J,T) =g= 0;

total_supply(T)..     uu(T) =e= sum(K,u(K,T));

demand(T)..           uu(T) =e= delta(T) * p(T)
                      + a(T);

supply(J,T)..         lambda(J,T)=g=(rho(J)**(ord(T)-1)) *
                      (p(T) + u(J,T) * delta(T));

abatement(J,T)..     (rho(J)**(ord(T)-1)) * (c(J,T) *
                      q(J,T)**3 + beta(J,T) * q(J,T)**2 + d(J,T) * q(J,T)
                      + tc(J) * q(J,T))
                      =g= lambda(J,T);

state_eq(J,T)..       x0(j)$T0(T) + x1(j)$T1(T) + x2(j)$T2(T) +
                      x3(j)$T3(T) + x(J,T-1) - u(J,T) +
                      q(J,T) - tar(J,T) =e= x(J,T);

costate_eq(J,T)..     lambda(J,T) =e=
                      (pi(J)*(rho(J))**(4))$TT(T) + lambda(J,T+1) + nux(J,T);

total_abat(T)..       r(T) =e= sum(J,q(J,T));

total_bank(T)..       b(T) =e= sum(J,x(J,T));

model hotair/ supply.u, demand.p, abatement.q, total_supply.uu,
costate_eq.lambda, state_eq.x, posix.nux, total_abat, total_bank/;

T0(T) = yes$(ord(T) eq 1);

T1(T) = yes$(ord(T) eq 2);

T2(T) = yes$(ord(T) eq 3);

T3(T) = yes$(ord(T) eq 4);

TT(T) = yes$(ord(T) eq 4);

solve hotair using mcp ; display u.l, q.l, x.l, p.l, nux.l,
lambda.l, uu.l, r.l, b.l ;

```