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A two-level dynamic game of carbon emission trading between Russia, China, and Annex B countries

A. Bernard[a], A. Haurie[b], M. Vielle[c], L. Viguier[d,*]

[a]*French Ministry of Equipment, Transportation and Housing, Tour Pascal B, 92055 La Défense Cedex 04, France*
[b]*HEC-Geneva, Uni-Mail, 40 Blvd. du Pont-d'Arve, CH-1211 Geneva 4, Switzerland*
[c]*CEA-LERNA, Manufacture des Tabacs, 21 Allée de Brienne, 31000 Toulouse Cedex, France*
[d]*Lombard Odier Darier Hentsch & Cie 11 Rue de la Corraterie 11 1204 Geneva, Switzerland*

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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 emission permits created by the Kyoto Protocol. The model uses a formulation of (i) a demand function for permits from Annex B countries and (ii) 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 emission trading market is thus assessed.

JEL classification: C73; D58; H41; Q25

Keywords: Dynamic games; Cournot–Nash equilibrium; Computable general equilibrium modeling; Climate change; Kyoto Protocol; Emission trading; Russia; China

*Corresponding author.
E-mail addresses: Alain.Bernard@equipement.gouv.fr (A. Bernard), alain.haurie@hec.unige.ch (A. Haurie), mvielle@cict.fr (M. Vielle), laurent.viguier@lodh.com (L. Viguier).

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1. Introduction

The aim of this paper is to propose a computable economic model of the strategic interactions between Russia and developing countries (DCs), in particular China, in international markets for carbon emission permits created by the Kyoto Protocol (UNFCCC, 1997). This model provides an assessment of the impact of this competition on the pricing of emission permits. We assume that some DCs will participate in future climate negotiations of the Kyoto Protocol and be able to sell emission permits on the international market. We also assume that the rest of the world will behave as a passive set of players integrating the emission permits in their production decisions according to the rules of a time-stepped[1] competitive economic equilibrium. A particular feature of the Kyoto Protocol is the large quantity of emission rights granted to Russia, since they were based on historic levels. Due to the collapse of the traditional industrial sectors in Russia, these emission rights – also called '*hot air*' – are now available at no cost. The agreement allows Russia to bank these emission rights and optimize over time their sale on the international market. This feature gives a dynamic structure to this oligopolistic competition for selling emission permits to other countries. We formalize it as a dynamic multistage game for which we compute an open-loop Nash equilibrium solution (Başar and Olsderh, 1989; de Zeeuw and van der Ploeg, 1991; Dockner et al., 2000). Differential game models have already been used successfully in environmental economics as e.g. in the fishery games[2] and more recently to analyze the acid rain game (Maler and de Zeeuw, 1998). In the Kyoto Protocol context Loschel and Zhang (2002) 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 Coase (1937) in his seminal paper 'The Nature of the Firm'. Transaction costs refer to the cost of providing for some good or service through the market rather than from within the firm.[3] Several authors have commented on the potential importance of transaction costs in tradable permits markets (Hahn and Hester, 1989; Stavins, 1995).[4] Stavins (1995) identifies three potential sources of transaction costs in tradable

[1]This means that the equilibrium is not dynamic and the investment strategies are fixed.

[2]See Kaitala (1986), Hamalainen et al. (1986) and Benchekroun and Long (2002) as a brief sample of the large literature on the topic.

[3]In 'The Problem of Social Cost', Coase (1998) 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'.

[4]See also the U.S. experience on SO_2 allowance trading (Joskow et al., 1998) and RECLAIM Trading Credits for NO_x and SO_x (Dudek and Wiener, 1996).

permit markets: '(1) search and information; (2) bargaining and decision; and (3) monitoring and enforcement, all these categories can be interpreted as representing cost due to lack of information'. In its global formulation our model is similar to the one proposed by Nagurney and Kanwalroop (2000) except that it does not deal with a spatially distributed pollutant and it has a dynamical two-level structure, where two players 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 stocks of emission permits banked by Russia and the dominant DC, China, respectively. The time horizon on which Russia and DCs compete to sell emission rights to other countries is 2010–2030. Each player has three control variables at its disposal that are (i) the rate of permits banking, (ii) the amount of permits supplied, and (iii) the emissions abatement levels, respectively. The equilibrium decisions by the two players are driven by the functions describing the demand for permits from other countries and by their respective marginal abatement cost (MAC) functions. These functions will be themselves obtained from two other models, GEMINI-E3 and POLES, respectively. GEMINI-E3 is a multi-region and multi-sector computable general equilibrium (CGE) model of the world economy (Bernard and Vielle, 2003) that will provide an estimate of the demand function for emission permits at each period of time. POLES is a partial equilibrium model of the world energy system (Criqui, 1996) that will be used to estimate MAC curves 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 emission market. In our scenarios, the emission permits game takes place between Russia and China, knowing that China is likely to be the main exporter of emission permits in a full global trading regime (Ellerman et al., 1998; Criqui et al., 1999; Zhang, 2000).

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 (Ferris and Pang, 1997). In Section 4 we discuss the calibration of the model based on simulations obtained from the GEMINI-E3 and POLES models. Section 5 presents the simulation results. A duopoly scenario is compared with a case where Russia acts as a monopoly in the emission market. Due to the large uncertainty around parameter 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 CDM 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 Parties committed to reducing, either individually or jointly, their total emissions of six greenhouse gases (GHGs) by at least 5% within the period 2008–2012, relative to these gases' 1990 levels. By 'Annex B Parties' one refers to the group of developed countries comprising OECD (as defined in 1990), Russia, and Eastern Europe. The Protocol also establishes three 'flexibility mechanisms' known as *joint implementation* (JI), the *clean development mechanism* (CDM), and *international emission trading* (IET). These mechanisms are designed to help Annex B Parties cut the cost of meeting their emission targets by taking advantage of opportunities to reduce emissions, or increase GHG removals, that cost less in other countries than at home[5]:

- Through IET, an Annex B Party may sell emission credits to another Annex B Party that finds it relatively more difficult to meet its emission target.
- Through JI, an Annex B Party may implement a project that reduces emissions (e.g. an energy efficiency scheme) or increases removals by sinks (e.g. a reforestation project) in the territory of another Annex B Party, and count the resulting emission credits against its own target.
- Through the CDM, Annex B Parties can promote sustainable development by financing emission-reduction projects in DCs in return for credit against their Kyoto targets.

The Protocol is subject to ratification by Parties to the Convention. It shall enter into force on the 90th day after the date on which not less than 55 Parties to the Convention, incorporating Annex B 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. As of 30 September 2004, the Protocol has been ratified by 26 states and regional economic integration organizations representing 44.2% of the total CO_2 emissions of Annex B parties in 1990. With the U.S. not intending to ratify (36% of Annex B emissions), the 55% threshold can only be met with the participation of Russia (17%). On September 2004, the Russian cabinet forwarded the Kyoto Protocol to the Russian Parliament (or Duma) for ratification.

The U.S. withdrawal from the Kyoto Protocol changes dramatically the character of the agreement.[6] With the U.S. out, the international market for GHG emission permits may be at risk. Using the MIT-EPPA model, Babiker et al. (2002) estimate that Annex B GHG emissions may increase by around 9% under the Kyoto–Marrakesh agreement without the U.S., and that the international carbon price might fall below \$5 per ton of carbon if all Russian 'hot air' were freely traded, and if Annex B countries made full use of the additional Article 3.4 sinks. Indeed, a particular feature of the Kyoto Protocol is the large quantity of emission rights

[5]For more details, see http://unfccc.int/.

[6]Since the withdrawal from international negotiations, the American administration is expected to bring a 'constructive position' to the ongoing Kyoto Protocol negotiations. On February 2001, President Bush has presented a voluntary plan to reduce GHG intensity by 18% over the next 10 years. It has been shown that this plan could be easily reached, under realistic hypothesis, without any specific climate change policy implementation (Viguier, 2002).

granted to Russia. In this Protocol Russia is committed to recover the 1990 levels for its GHS emissions between 2008 and 2012. After the fall of the Soviet Union, Russia experienced a dramatic decline in economic activity and a large decrease in carbon emissions. Due to this collapse, emission rights are projected to be far above baseline emissions in the near future. These emission credits are available at no cost to Russia, without any effective CO_2 abatement; this is why they are also called 'hot air'.

In that context, strategic behavior by Russia in an IET 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 (Bohringer, 2001; de Moor et al., 2002; Buchner et al., 2002; Babiker et al., 2002). In a simple 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 DCs) and without exploiting the possibility to bank emission permits. According to the authors, when Russia is assumed to act as a monopoly, the supply of permits is reduced by 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 (Manne et al., 1995). They show that it is profitable for Russia to defer a substantial share of 'hot air' for later use.[7] 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). Similarly, Bernard and Vielle (2002) and Bernard et al. (2003) 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 two different CGE models (GEMINI-E3 and EPPA-MIT), these studies show that short run carbon prices (2010) are not strongly 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 Bernard and Vielle (2002), the amount of CDM projects competing in each period of time with Russia's emission permits is set exogenously and DCs strategic behavior is not modeled. However, one might expect strategic interactions between Russia and DCs in carbon markets.

Even if Russia may currently envision a monopolistic position in the international market for tradable emission permits, it might be soon in competition with DCs via the supply of CDM or even their direct participation in emission trading. Annex B countries may choose to develop CDM projects in DCs rather than importing emission permits from Russia. Indeed, 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 the post-Kyoto regime. The model that is presented in this

[7]Knowing 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.

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 emission permits. These stocks can be replenished via an abatement activity.

3.1. The equations

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

- *Player* 1: It represents Russia which benefits from 'hot air'. The following variables and parameters enter into the description of player 1:
  β_1 discount factor for player1
  $x_1(t)$ 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.
  In the above list of parameters and variables, the time function $h(t)$, which is exogenously given, represents the amount of credited 'hot air' emissions abatement at each time t. We assume $h(t) \geqslant 0$ if $t < T$ and $h(T) = 0$. The dynamical system representing player 1 is defined as follows:

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

s.t.

$$x_1(t+1) = x_1(t) - u_1(t) + h(t) + q_1(t), \tag{2}$$

$$x_1(0) = 0, \tag{3}$$

$$u_1(t) \geqslant 0, \tag{4}$$

$$x_1(t) \geqslant 0. \tag{5}$$

- *Player* 2: It represents a large developing country (typically China) which may develop its own market of emission 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
π_2 terminal value of the stock of permits
θ period at which China may join the market.
The dynamical system representing Player 2 is defined as follows:

$$\max \sum_{t=0}^{T-1} \beta_2^t [p(t)u_1(t) - c_2(q_2(t))] + \beta_2^T \pi_2 x_2(T) \tag{6}$$

s.t.

$$x_2(t+1) = x_2(t) - u_2(t) + q_2(t), \tag{7}$$

$$x_2(0) = 0, \tag{8}$$

$$u_2(t) \geqslant 0, \tag{9}$$

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

$$x_2(t) \geqslant 0. \tag{11}$$

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

$$p(t) = D(u_1(t) + u_2(t)). \tag{12}$$

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

3.2. Information structure

We look for an equilibrium solution, assuming an open-loop information structure. It means that the competing agents select an open-loop control, i.e., a time schedule for their supply of emission permits over the planning horizon $0, 1, \ldots, T-1$. The possible alternative would have been to assume a feedback information structure, where the supply of agent i would have been defined as a function $\tilde{u}_i(t, x_1, x_2)$ describing a reaction to the observed stock of banked permits in the two regions. The great advantage of the feedback formulation is that it yields an equilibrium concept which satisfies a dynamic programming equation and which is therefore time consistent and subgame perfect. On the other side, this information structure does not yield to an easy numerical solution implementation. The open-loop structure, although it lacks subgame perfectness, provides several advantages to the modeler. First there are well known existence and uniqueness conditions for the dynamic equilibrium. Due to the standard structure 'à la Cournot' and the linearity of the state equations we may assume that the conditions for existence and uniqueness of a Nash equilibrium will easily be met (Rosen, 1965).

Under these conditions a numerical approximation of the equilibrium can be obtained by implementing mathematical programming techniques (solutions of variational inequalities or of nonlinear complementarity problems). As demonstrated in the coming developments there are efficient codes permitting the computation of these solutions. Another advantage of the open-loop information structure is that it is time consistent, so no revision of the equilibrium policy should occur, as long as the system is not perturbed. It is therefore adapted to the description of planning decisions by states or nations, in a deterministic environment. An extension of the open-loop information structure to a stochastic environment has also been proposed under the name of S-adapted information structure as discussed by Haurie et al. (1990) and Haurie and Moresino (2002). (A stochastic variant of the model studied in this paper with the S-adapted information structure can be found in Haurie and Viguier, 2003.) In summary a feedback equilibrium solution seems less attractive than the open-loop one because it is much more difficult to compute and because it does not necessarily better represent the planning decisions of the players.

3.3. 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 used the PATH solver (Ferris and Munson, 2000).

- *Player* 1: We introduce the Hamiltonian

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

  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:

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

$$-\frac{\partial}{\partial u_1}H_1(t)u_1(t) = 0, \quad u_1(t) \geqslant 0, \quad -\frac{\partial}{\partial u_1}H_1(t) \geqslant 0, \quad t = 0, \ldots, T-1, \tag{15}$$

$$-\frac{\partial}{\partial q_1}H_1(t) = \beta_1^t[c_1'(q_1(t))] + \lambda_1(t+1), \quad t = 0, \ldots, T-1, \tag{16}$$

$$-\frac{\partial}{\partial q_1}H_1(t)q_1(t) = 0, \quad q_1(t) \geqslant 0, \quad -\frac{\partial}{\partial q_1}H_1(t) \geqslant 0, \quad t = 0, \ldots, T-1, \tag{17}$$

with

$$\lambda_1(t) = \frac{\partial}{\partial x_1} H_1(\lambda_1(t+1),$$
$$\mu_1(t), x_1(t), u_1(t), q_1(t)) = \lambda_1(t+1) + \mu_1(t), \quad t = 0, \ldots, T-1, \tag{18}$$

$$\lambda_1(T) = \beta_1^T \pi_1, \tag{19}$$
$$\mu_1(t) x_1(t) = 0, \quad x_1(t) \geqslant 0, \quad \mu_1(t) \geqslant 0, \quad t = 0, \ldots, T-1. \tag{20}$$

- *Player* 2: Similarly we define the Hamiltonian

$$\begin{aligned} &H_2(\lambda_2(t+1), x_2(t), u_2(t), q_2(t)) \\ &\quad = \beta_1^t [p(t) u_2(t) - c_1(q_2(t))] \\ &\qquad + \lambda_2(t+1)(x_2(t) - u_2(t) + q_2(t)) + \mu_2(t) x_2(t) \end{aligned} \tag{21}$$

and the following conditions must hold:

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

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

$$-\frac{\partial}{\partial q_2} H_2(t) = \beta_2^t [c_2'(q_2(t))] + \lambda_2(t+1), \quad t = 0, \ldots, T-1, \tag{24}$$

$$-\frac{\partial}{\partial q_2} H_1(t) q_2(t) = 0, \ \ q_2(t) \geqslant 0, \quad -\frac{\partial}{\partial q_2} H_2(t) \geqslant 0, \quad t = 0, \ldots, T-1 \tag{25}$$

with

$$\lambda_2(t) = \frac{\partial}{\partial x_2} H_1(\lambda_2(t+1), \tag{26}$$
$$\begin{aligned} &\mu_2(t), x_2(t), u_2(t), q_2(t)) = \lambda_2(t+1) + \mu_2(t), \\ &\quad t = 0, \ldots, T-1, \end{aligned}$$
$$\lambda_1(T) = \beta_2^T \pi_2, \tag{27}$$
$$\mu_2(t) x_2(t) = 0, \quad x_2(t) \geqslant 0, \quad \mu_2(t) \geqslant 0, \quad t = 0, \ldots, T-1. \tag{28}$$

4. Calibration of the model

The basic data used to calibrate the model are:

- the *demand for flexible instruments* by Annex B countries (other than Russia and without the U.S.); 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 emission permits from Russia or CDM from China);

- the *MAC curves* in Russia and China, as a function of emissions in the reference case, the magnitude of the substitutions and demand elasticities, and adjustment dynamics (Weyant, 1999);
- the amount of 'hot air' in Russia, as a function of emission trajectories in the Business-As-Usual scenario in Russia, and emission targets in the Kyoto Protocol (2010) and in the post-Kyoto architecture (up to 2030).

To do the calibration, we use simulation results of a CGE model, GEMINI-E3 (Bernard and Vielle, 1998, 2000, 2003), and a partial equilibrium model of the world energy system, POLES (Criqui, 1996). Specifically, we simulated each of these models across a wide range of carbon limits.

4.1. The CGE model

GEMINI-E3 is a multi-country, multi-sector, time-stepped CGE model incorporating a highly detailed representation of indirect taxation (Bernard and Vielle, 2003). 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 which is 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 MAC, i.e., the welfare loss of a unit increase in pollution abatement. In addition to a comprehensive description of indirect taxation, the model simulates 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 measured.[8]

4.2. The energy system simulation model

POLES is a global partial equilibrium model of the world energy system with 30 regions. POLES produces detailed world energy and CO_2 emission projections by region through the year 2030. POLES combines some features of 'top-down' models since prices play a key role in the adjustment of most variables, but retains a level of details in the treatment of technologies that is 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 (Criqui, 1996). MAC curves for CO_2 emission 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

[8]The real exchange rate between two countries is the relative price of the 'numeraire' 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.

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 (Blanchard et al., 2003; Criqui et al., 1999; Criqui and Viguier, 2000).

4.3. Derived demand curves

Fig. 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. These curves have been obtained by fitting polynomial regressions to a set of outputs from GEMINI-E3 where different permit prices are imposed.

4.4. MACs in Russia and China

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 emissions.[9]

MAC curves for Russia are taken from GEMINI-E3, whereas MAC curves for China (not available in GEMINI-E3) are obtained from the POLES model. Even if the two models belong to different paradigms, it has been shown that their MAC curves are comparable (Vielle, 2002), in particular if we interpret MAC curves as representing only the ‘primary costs’ of the carbon policy. It is justified to use these curves if we assume that an industry-level emission permits system is implemented rather than a government-level emission permits system. In that case, private entities do not take into account the social cost but the private costs of their abatement decisions (Babiker et al., 2004). Welfare costs[10] and international trade effects[11] of climate policies will thus not be reported in this study.

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

[9]As explained by Ellerman et al. (1998), a CGE model can produce a ‘shadow price’ for any constraint on carbon emissions for a given region in a given period of time. A MAC curve plots the shadow prices corresponding to different levels of emission reduction. MAC curves are upward-sloping: the shadow price of emission reduction rises with the level of emission reduction.

[10]In order to measure the welfare impact of IET in a second-best world, one may 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; see Goulder (1995), Goulder et al. (1999), Babiker et al. (2003) and Bernard and Vielle (2003).

[11]It has been shown in Bernard et al. (2003) that the Russian behavior on the emission trading market has a very limited impact on its terms of trade.

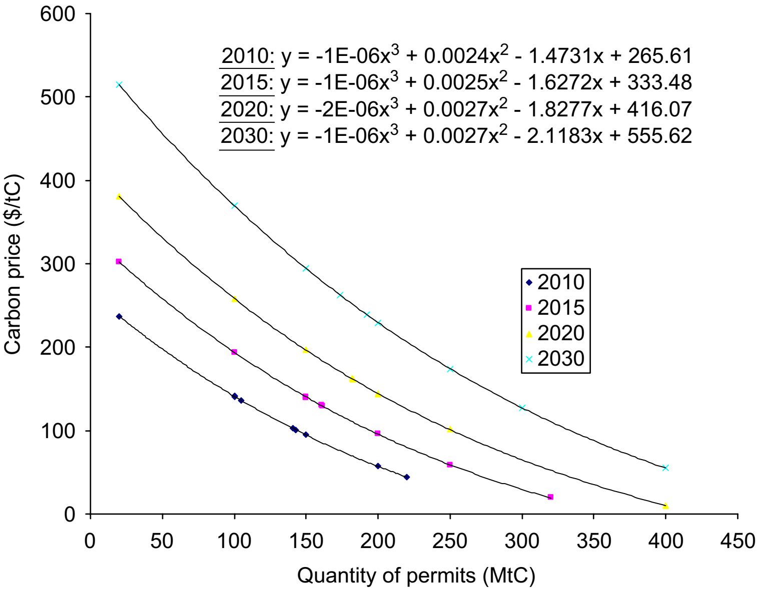

Fig. 1. Demand functions from GEMINI-E3.

4.5. 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 growth forecasts. The amount of 'hot air' is estimated to range from 150 to 500 MtC in 2010 (Paltsev, 2000). The U.S. Department of Energy (DOE) predicts, for a baseline scenario, annual energy-related carbon emissions in the Former Soviet Union to change from approximately 1036 MtC in 1990 to 745 MtC in 2010, and then 884 MtC in 2020 (EIA, 2002). According to the same DOE report, 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 (Bernard et al., 2003). 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 emission permits game described in Section 3.

Table 1
Simulation results for the two scenarios

	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

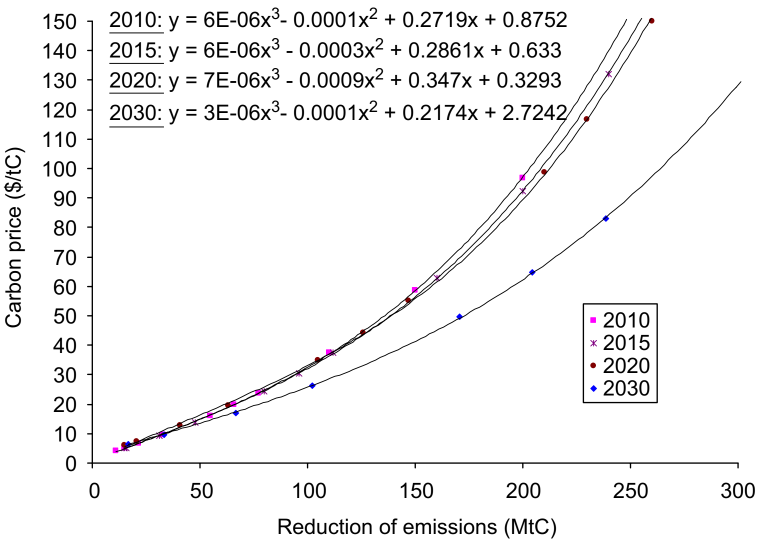

Fig. 2. MAC curves of Russia from GEMINI-E3, 2010–2030.

In the two cases, the demand of emission permits is assessed under a ‘Kyoto Forever’ scenario, implying that Annex B countries (except the U.S.) are committed to a constant level of emissions over time – the one sets in the Protocol – while non-Annex B countries remain free of any commitment. We suppose that emission permits are freely tradable in

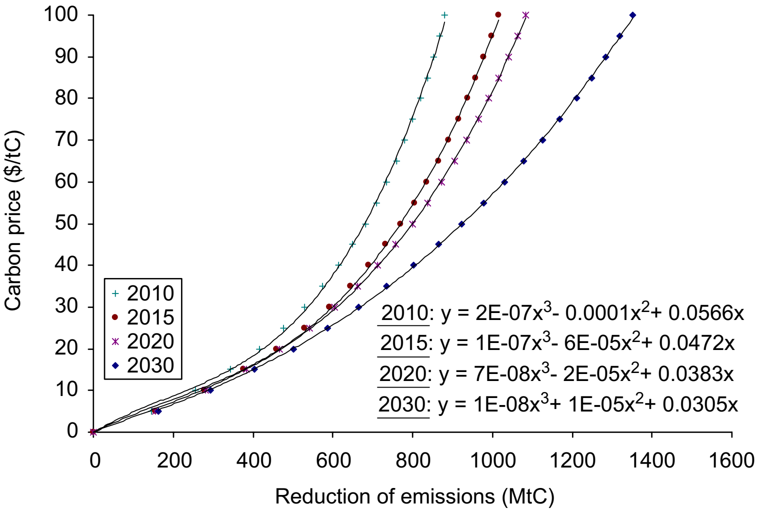

Fig. 3. MAC curves of China from POLES, 2010–2030.

the international market (no ‘concrete ceilings’[12] on emission trading). It is also assumed that Russia can freely trade its hot air, and that emission 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 two base cases. The impacts of China’s participation in the post-Kyoto regime, and transaction costs on the emission markets, will be assessed further.

Table 1 reports simulation results in the two base cases. In the monopoly scenario, emission permits sold by Russia go from 110 MtC in 2010 to 230 MtC in 2030 (Fig. 4). The size of the carbon market increases dramatically when China is allowed to enter the market. The total supply of emission permits ranges from 160 MtC in 2010 to 300 MtC in 2030. Russia’s exports of emission 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.

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

[12]‘Concrete ceilings’ is a rule that has been proposed by the European Union to guarantee a minimum emission 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 Criqui et al. (1999).

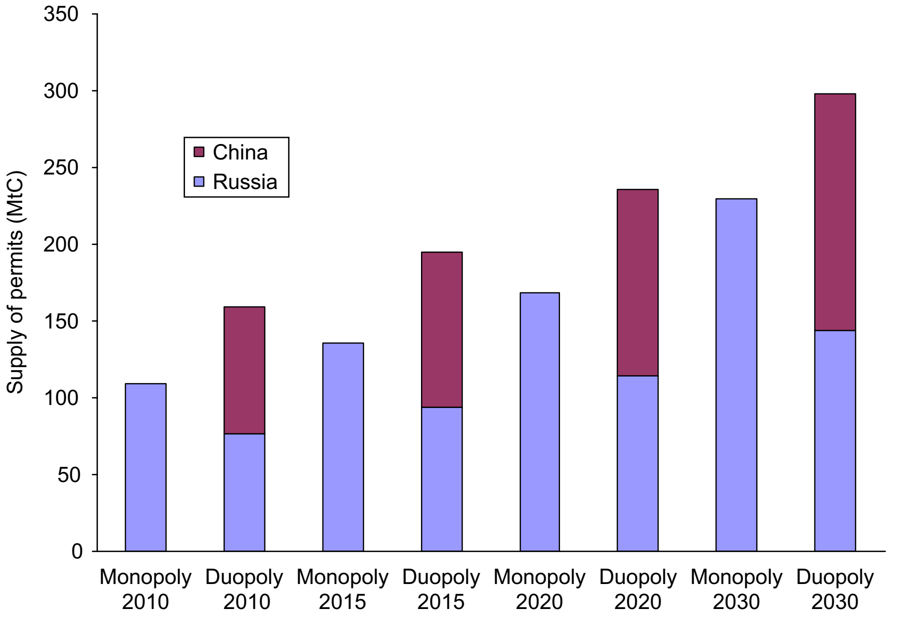

Fig. 4. Supply of CO_2 permits (monopoly and duopoly cases).

As shown in Fig. 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 CO_2 emission markets. 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 emission permits since the increase of permit prices over time is limited (compared to the 5% discount rate).

As indicated before, it has been argued that the permit price might be close to zero in 2010 due to the U.S. withdrawal from the Kyoto Protocol. In other studies (Bohringer, 2001; Babiker et al., 2002; Blanchard et al., 2002), the permit price has been predicted to range from 20$/tC to 60$/tC in 2010 if we assume a myopic monopolistic behavior of Russia. Bernard et al. (2003) have shown that this price 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 these 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 (Fig. 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$/tC in 2010, the permit price rises slowly to 128$/tC in 2030.

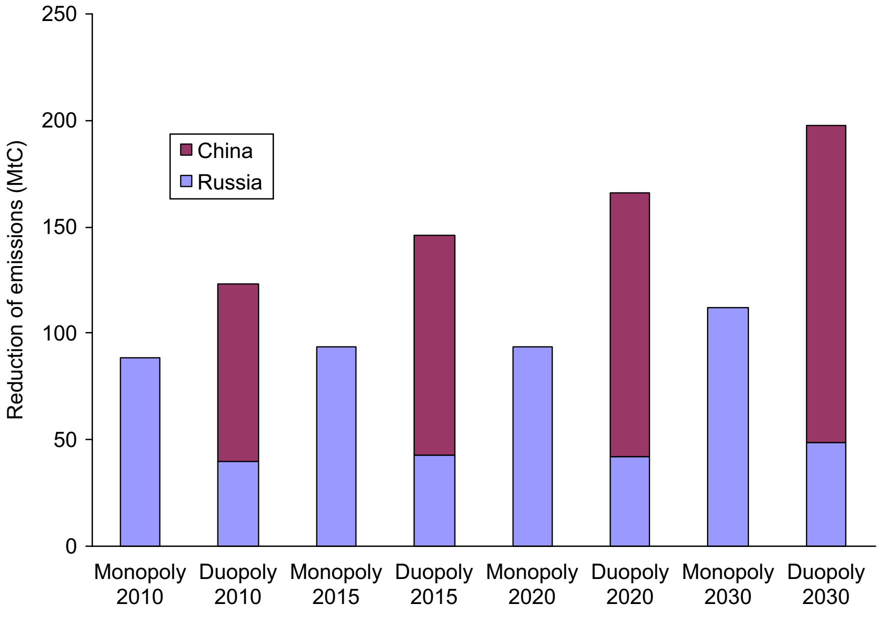

Fig. 5. Reduction of carbon emissions (monopoly and duopoly cases).

6. Sensitivity analysis: transaction costs and participation of China

In this section, we assess the sensitivity of these results to parameters variations. The two most uncertain parameters which are likely to have an impact on the price of emission permits are (i) the level of participation of China in the international effort to curb GHG emissions, and (ii) the transaction costs associated with CDM projects.

6.1. Transaction costs

U.S. experience with emission trading shows that transaction costs might reduce the cost-effectiveness of the instrument. For example, transaction costs in the *Emission Trading Program* (ETP) market[13] have been substantial, due to both their bilateral nature and the difficulty in quantifying eligible emission reductions (Dudek and Wiener, 1996). By contrast, the SO_2 allowance trading system established by the Clean Air Amendments of 1990 was explicitly designed to minimize transaction costs.[14] Current experiences in the

[13]The ETP has been established by the U.S. 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.

[14]The 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 (McLean, 1997; Joskow et al., 1998).

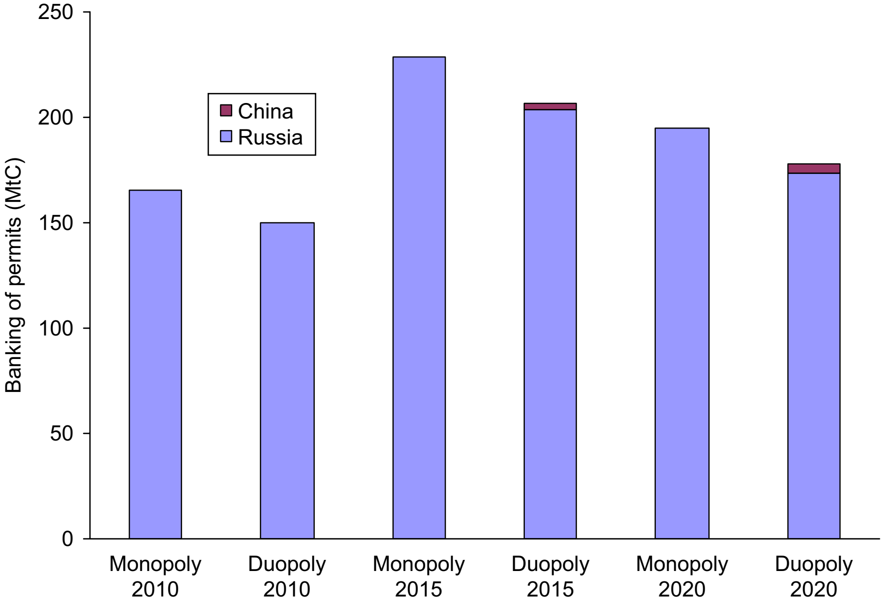

Fig. 6. Banking of CO_2 permits (monopoly and duopoly cases).

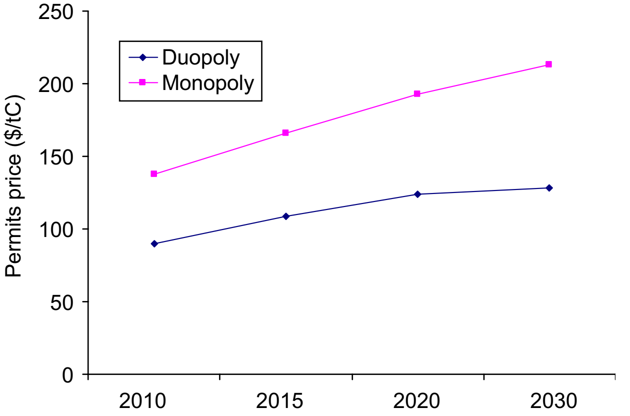

Fig. 7. Price of CO_2 permits (monopoly and duopoly cases).

pilot phase of JI[15] show that transaction costs can seriously erode the cost-saving potential of JI-type projects (Dudek and Wiener, 1996). There is little empirical evidence concerning transaction costs associated with CDM projects (Michaelowa et al., 2003; Jotzo and Michaelowa, 2002). Michaelowa et al. (2003) list the

[15]The JI allows any party operating under FCCC Article 4(2)(a) to undertake its GHG abatement activities five wherever conditions and partners are most welcoming.

transaction costs linked to CDM and JI projects. Some of them occur during the pre-implementation phase of the project (i.e., exchange of permits). We find in this group the search costs, the negotiation costs, the validation costs, the review costs and the registration costs. Other transaction costs occur after the agreement between the buyer and the seller during the completion of the transaction. The monitoring costs, the verification costs, and the certification costs belong to this category. Moreover, the absence of clear ground rules and guidelines for baseline assessment can inhibit private-sector participation in CDM and prevent DCs from playing a lead role in the project identification and development process.

There are different ways to introduce transaction costs in the model. One can use a *price approach* that consists in adding an extra cost (or fee) per ton of emission reduction (Jotzo and Michaelowa, 2002). One might opt for a *quantity approach*: scaled back economy-wide estimates of emission reductions realized at a given level of carbon tax to take account of the fact that only a very limited subset of possible emission 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 us say energy-intensive industries and the energy sector (*Sectoral approach*). Finally, we could limit CDM projects to technologies that could be easily transfer in DCs (*Technology approach*).

In this study, we use the *price approach*. Transaction costs are introduced directly in the MAC curves by applying a fee to CDM projects in China. The MAC function used in the model is

$$\alpha q^3 + \beta q^2 + (\gamma + \delta)q, \tag{29}$$

where q stands for the reduction of CO_2 emissions, and where δ is the transaction costs parameter. In our simulations, δ ranges from 0 to 0.40. As shown in Fig. 8, when we assume no transaction costs, the potential for CDM in China in 2010 is 100 MtC at 4.86\$/tC. When $\delta = 0.4$, the potential for CDM is only 100 MtC at 44.86\$/tC in 2010.

6.2. Participation of China

In the two base cases, it was assumed that China has no target for carbon emissions, and that the sales of permits come from voluntary abatement in relation to its emission baseline. However, one might expect some DCs, including China, to participate in post-Kyoto negotiations. Various approaches have been proposed to differentiate GHG emission reductions worldwide. One of the candidate for allocating emission reductions across countries in the post-Kyoto architecture is the 'Soft-Landing' approach (Blanchard et al., 2003); 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 emission 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

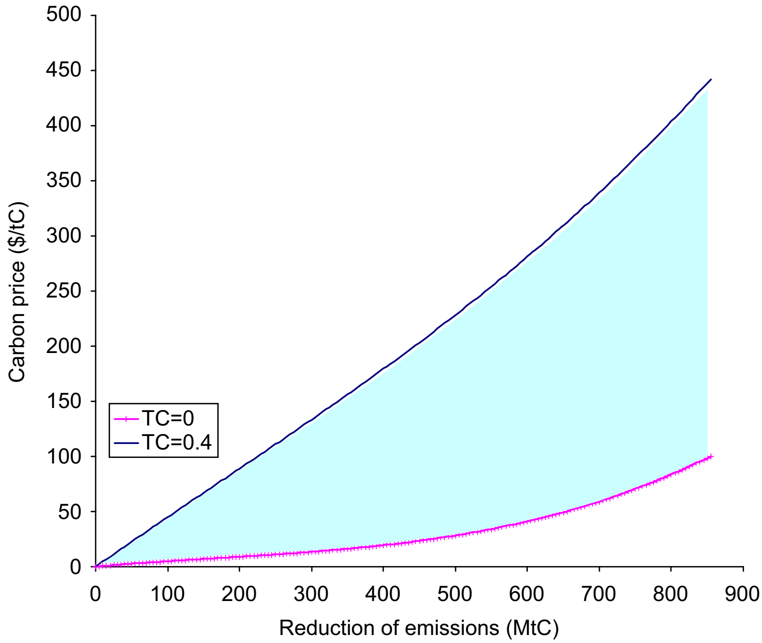

Fig. 8. CDM potential in China, 2010.

emissions are 2.4 Gt in 2030 and the emission reduction required to stabilize China's emissions in 2030 is 274 MtC (Blanchard et al., 2003). In this study, we use the Soft Landing scenario computed in POLES as the upper bound. As shown in Figs. 9 and 10, China's emission reductions range from 0 to 300 MtC in our simulations.

6.3. Simulation results

Table 2, Figs. 9 and 10 summarize the supply of emission permits from China 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 emission reductions. As long as transaction costs stay relatively low, China might accept emission targets in the post-Kyoto architecture without reducing its permits sales. China sells 83 MtC in 2010 in the no transaction cost and no commitment scenario (the base case). China's supply might be reduced by 40% in 2010 and 73% in 2030 when we assume transaction costs and a commitment to stabilize emissions in 2030. For example, 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 $\delta = 0.2$ and a 150 MtC commitment in 2030.

Table 3, Figs. 11 and 12 show that transaction costs and the participation of China in emission reductions might have a significant impact on the price of emission

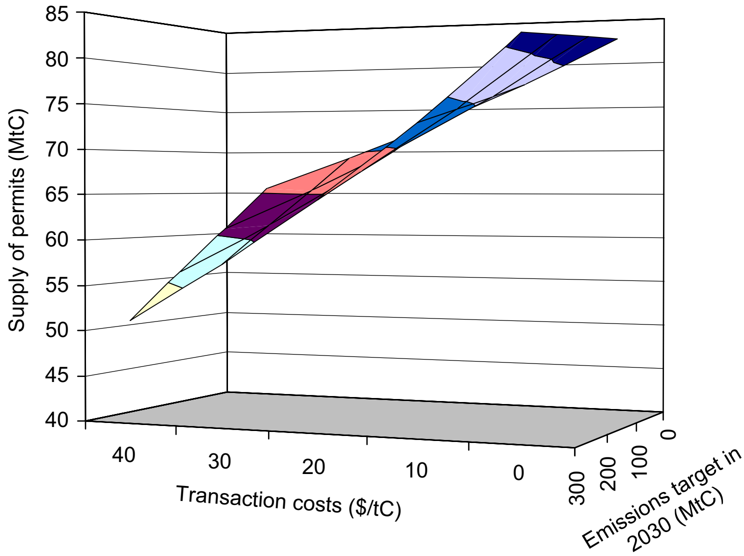

Fig. 9. Sensitivity of China's supply to transaction costs and China's participation in 2010.

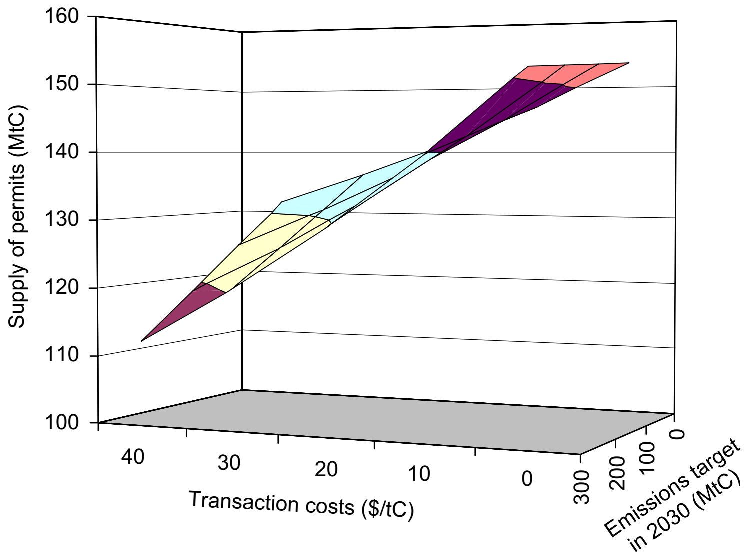

Fig. 10. Sensitivity of China's supply to transaction costs and China's participation in 2030.

permits. In 2010, the permit price may increase from 90$/tC in the base case to 116$/tC with high transaction costs and a stabilization of China's emissions in 2030. In 2030, the permits price rises from 128$/tC to 163$/tC.

Table 2
Supply of permits under different transaction costs (0–0.4) and CO_2 reduction targets in China (0–300 MtC)

MtC	Transaction costs (δ)									
	Russia					China				
	0.4	0.3	0.2	0.1	0	0.4	0.3	0.2	0.1	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 4 shows the total revenues 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 by 2010 if we assume zero transaction costs ($\delta = 0$) associated with CDM projects and no reduction targets for China in the post-Kyoto regime. 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 target 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 the parameter values in the long run. Trading gains range from US$ 9.1 billion to US$ 9.9 billion in 2030 whatever the 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 base case when China is committed to stabilize its emissions by 2030 and when high transaction costs are applied ($\delta = 0.4$).

Table 3
Price of permits under different transaction costs (0–0.4) and CO_2 reduction targets in China (0–300 MtC), in $/tC

MtC	Transaction costs (δ)				
	0.40	0.30	0.20	0.10	0
2010					
300	115.7	110.0	104.0	97.6	90.8
200	112.7	107.6	102.3	96.6	90.5
100	109.6	105.2	100.5	95.5	90.2
0	106.6	102.8	98.8	94.5	89.9
2015					
300	135.7	129.8	123.5	116.8	109.5
200	132.6	127.3	121.7	115.7	109.2
100	129.4	124.8	119.8	114.5	108.9
0	126.2	122.2	118.0	113.4	108.6
2020					
300	153.5	147.0	140.1	132.8	124.9
200	150.0	144.3	138.1	131.6	124.5
100	146.6	141.5	136.1	130.4	124.2
0	143.1	138.8	134.1	129.2	123.9
2030					
300	163.3	155.7	147.5	138.9	129.6
200	159.2	152.4	145.2	137.5	129.2
100	155.1	149.2	142.8	136.0	128.8
0	151.1	145.9	140.5	134.6	128.4

7. Conclusion

In this paper, we have presented a computable two-level dynamic game of carbon emission trading between Russia, China, and Annex B countries. This model was calibrated using GEMINI-E3, which is a multi-country, multi-sector, dynamical-recursive CGE model developed to analyze climate change policies, and POLES, which computes a partial equilibrium of the world energy system in 30 regions.

In our simulations, it appears that the competition between Russia and China on the international market for carbon emissions should lower significantly the permit prices compared to the case where Russia acts as a monopoly. The introduction of transaction costs in China and the stabilization of China emissions by 2030 do not modify significantly the Russia's revenues from emission trading. These simulation results tend to show that the participation of DCs in an IET scheme with 'reasonable' abatement targets for them could be beneficial to both Annex B countries and DCs (Viguier, 2004).

Nevertheless, a high level of uncertainty remains in several parameters of the model; in particular the amount of 'hot air', MAC curves, emission targets in the post-Kyoto regime, etc. A stochastic equilibrium model in the line of the one

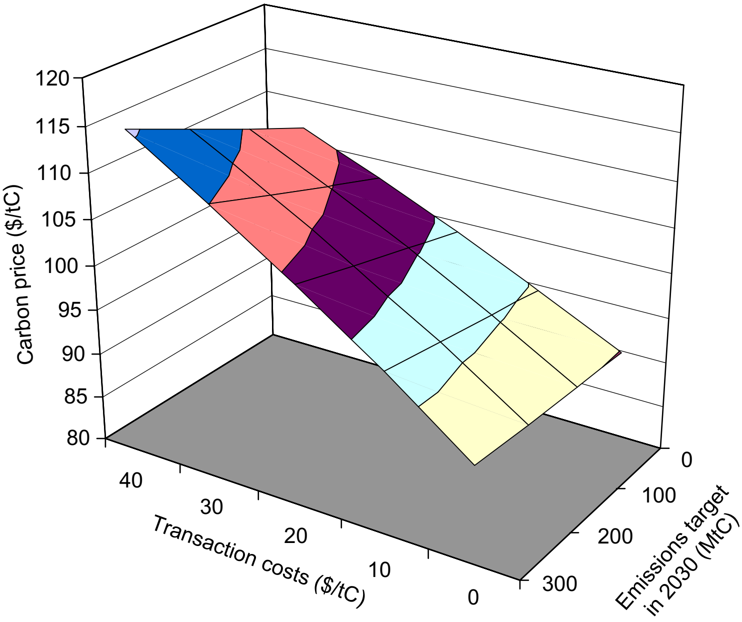

Fig. 11. Sensitivity of the CO_2 price to transaction costs and participation of China in 2010.

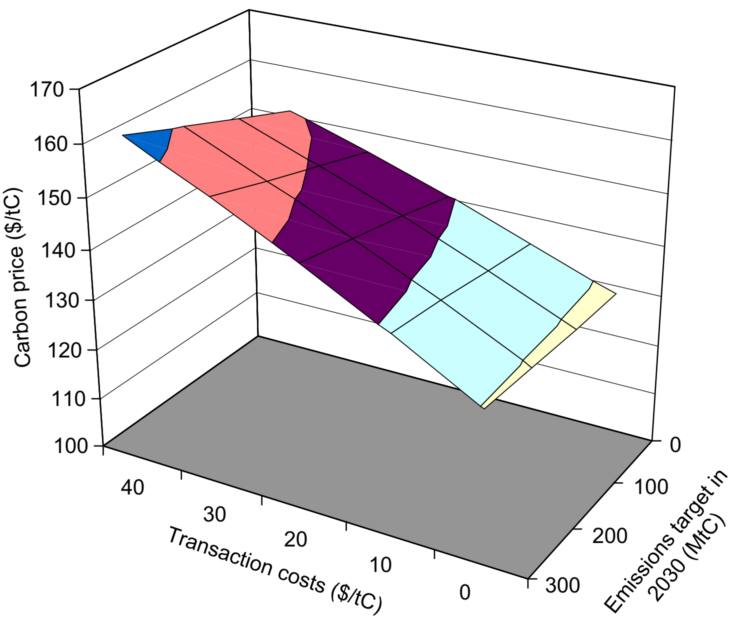

Fig. 12. Sensitivity of the CO_2 price to transaction costs and participation of China in 2030.

Table 4
Revenue from permit sales under different transaction costs (0–0.4) and CO_2 reduction targets in China (0–300 MtC), in US$ billion

MtC	Transaction costs (δ)									
	Russia					China				
	0.40	0.30	0.20	0.10	0	0.40	0.30	0.20	0.10	0
2010										
300	4.69	4.44	4.16	3.84	3.49	2.97	3.17	3.36	3.53	3.69
200	4.48	4.27	4.03	3.77	3.47	3.16	3.31	3.45	3.58	3.70
100	4.27	4.10	3.91	3.69	3.45	3.34	3.44	3.54	3.63	3.71
0	4.07	3.94	3.79	3.62	3.43	3.50	3.56	3.62	3.68	3.73
2010										
300	6.72	6.40	6.04	5.63	5.18	4.59	4.82	5.03	5.24	5.43
200	6.45	6.18	5.88	5.54	5.15	4.81	4.98	5.15	5.30	5.45
100	6.18	5.97	5.72	5.44	5.12	5.02	5.14	5.25	5.36	5.46
0	5.92	5.75	5.56	5.34	5.09	5.21	5.28	5.35	5.42	5.48
2020										
300	9.26	8.82	8.33	7.78	7.16	6.59	6.83	7.06	7.28	7.49
200	8.90	8.53	8.11	7.65	7.13	6.85	7.02	7.19	7.35	7.50
100	8.55	8.24	7.90	7.52	7.09	7.09	7.20	7.31	7.42	7.52
0	8.20	7.96	7.70	7.40	7.05	7.31	7.37	7.43	7.48	7.54
2030										
300	12.83	12.08	11.26	10.37	9.39	9.17	9.37	9.55	9.71	9.82
200	12.26	11.62	10.93	10.17	9.34	9.46	9.58	9.69	9.78	9.84
100	11.70	11.18	10.61	9.98	9.28	9.71	9.77	9.81	9.84	9.85
0	11.15	10.74	10.29	9.78	9.23	9.94	9.94	9.93	9.90	9.87

proposed by Haurie and Moresino (2002) has been studied by Haurie and Viguier (2003), when the random shocks are independent from the players controls. The extension to a stochastic framework where one endogenizes the decision of a DC to enter the permits market is still to be developed.

Acknowledgments

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