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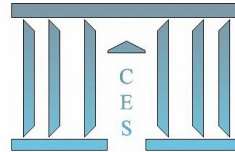
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International Emissions Trading Scheme and European Emissions Trading Scheme: what linkages? *

Natacha Raffin [†] and *Katheline Schubert* [‡]

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Résumé

La concomitance des périodes d'engagement (2008-2012) des marchés international et européen de permis pourrait engendrer des distorsions en termes de répartition de la charge environnementale entre les secteurs. En effet, les deux niveaux d'échange (gouvernemental et entrepreneurial) doivent rester cohérents, malgré leurs différentes caractéristiques. Pour atteindre leur objectif, les gouvernements européens devront instaurer une politique additionnelle qui consiste à taxer les émissions des secteurs non-assujettis. La taxe dépendra de l'effort réalisé au sein de l'UE-ETS. Nous proposons une modélisation de cette politique à double niveau, en nous concentrant sur le niveau des taxes dans les différents cas d'imbrication. Nous estimons les efforts qui seront demandés aux secteurs non-assujettis ainsi que les différents prix de carbone.

Mots-clef : Protocole de Kyoto, EU-ETS, Coexistence de marchés de permis échangeables domestique et international, prix du carbone et politique environnementale.

Codes JEL : Q53 ; Q58 ; Q28

Abstract

Simultaneity between commitment periods (2008-2012) of both International and European Emissions Trading schemes may generate distortions in terms of burden distribution among sectors. There will be two levels of trading (a country and an entity level), which both need to be consistent with one another, despite of their different designs. To reach international targets, European governments will adopt an additional policy. It consists in implementing a tax on emissions of non-covered sectors. The tax rates depend on the effort realized within the European market. We propose a modeling of this two-level environmental policy, focusing on the levels of tax rates in each case of linkage. We obtain empirical estimations of the efforts that could be demanded to non-covered sectors, and of the price(s) of carbon.

Keywords: Kyoto Protocol, EU-ETS, co-existence of domestic and international emissions trading systems, carbon price, environmental policy.

JEL Classification: Q53; Q58; Q28

1 Introduction

Simultaneity between commitment periods (2008-2012) of the International Emissions Trading scheme (hereafter IET) and the European Union Emissions Trading Scheme (hereafter EU-ETS) is likely to generate distortions in terms of distribution of the burden among sectors and among countries. Indeed, the features of these two emissions trading schemes are not the same. The first one is established on a country level whereas the second one is defined on an entity level. Besides, IET covers sectors not initially included in EU-ETS. To reach international targets, each European government will have to adopt an additional environmental policy concerning these latter sectors. This policy may consist in implementing a tax on emissions of sectors only included in the Kyoto Protocol. The level of such a tax would depend on the effort realized within the European market by the covered sectors. Anyhow, several carbon prices could coexist: an international price, a European price for covered sectors within EU-ETS, and domestic prices –the tax rates– for non-covered European sectors. This would induce distortions in the behavior of firms and states, and would certainly not contribute to the equity and the transparency of the whole carbon device.

We propose in this paper a modeling of this two-level environmental policy, focusing on the additional tax rate that could enable a European government to fulfill its international obligation in presence of a domestic market. It allows us to obtain empirical estimations of the efforts that will be demanded to polluting sectors in European countries, and to show how these efforts would be distributed, under different assumptions about the behavior of Europe on the international market. It also allows us to estimate the different carbon prices that could coexist.

Since February 2005, the Kyoto Protocol on Climate Change has entered into force. It implements an International Emissions Trading Scheme as a mechanism of flexibility to limit greenhouse gas emissions. The first commitment period will start in 2008 and last for five years. The main objective, for Parties members of Annex B¹, is to reduce the average level of emissions by 5.2 percent compared to the 1990 level. Each Party receives a pre-determined amount of allowances (*Assigned Amount Units* or AAU, expressed in metric tonnes of CO₂ equivalent) to fulfill its obligation notified in Annex A of the Treaty. These units or permits give a right to emit pollutants up to a bounded level. Each government is allowed to sell (or purchase) units on the international market to be in compliance. In this framework, Europe, considered as a “Party”, is required to reduce its emissions level by 8 percent by comparison to the initial level of 1990. In addition, the overall European objective of emissions reduction is distributed among European countries in the “*European Burden Sharing Act*”.

In spite of the fact that the international market is defined on a country level, the Treaty does not exclude the opportunity of implementing domestic trading systems in order to reach targets at least cost, according to Article 17. Thus, according to the Protocol, the European Commission decided in 2003 to implement a domestic environmental pol-

1. Annex B of the Treaty brings together OECD countries participating to the Protocol, plus eastern European countries and ex-soviet block countries, less the United States and Australia.

icy establishing a European Union Emissions Trading Scheme² (European Commission, 2003). The objective of EU-ETS is to lower the costs of compliance at the international level by gradually reducing emissions, and to enable entities to adapt themselves to a new instrument of environmental policy. This European market is thus established on an entity level. The first commitment period of EU-ETS began in 2005, and the second one will span over the years 2008-2012. Plants included in EU-ETS receive some units called *European Carbon Currency*, and can trade them. The European targets within EU-ETS are determined by each European government and reported in the National Allocation Plans. Each NAP is submitted to the approbation of the European Commission.

Hence, both systems will be operating during the same period, 2008-2012. So, there will be two levels of trading during this period: a country level and an entity level, which need to be consistent with one another (Butzengeiger *et al.*, 2001). Each European state will have to respect on the one side the European cap associated with EU-ETS, and on the other side the international target within IET.

However, the designs of these two systems are different. While the international system covers the six main greenhouse gases³, EU-ETS covers only CO₂ emissions. Moreover, the international market covers sectors not included in the European system such as transport, agriculture, waste and housing-tertiary, in addition to those included in EU-ETS such as energy activities, mineral industries, oil refineries.

In this paper, we focus on the behavior of a European government facing this double environmental constraint. As mentioned above, within EU-ETS, governments are required to determine the level of emissions reduction, taking into account their international objective. The abatement realized through EU-ETS will be taken into account for the international compliance at the end of the first commitment period, as IET covers emissions of sectors included in EU-ETS. This situation implies a distribution of the burden among covered sectors and sectors only included in IET. As notified by Godard (2005), if the domestic objective is low, then non-covered sectors will have to support the main part of the environmental constraint. Indeed, the presence of a domestic market generates distortions in terms of distribution of the burden both among sectors and among countries.

We consider that European governments will implement a tax rate on emissions of non-covered sectors, to ensure the international compliance. These tax rates will be the instrument that guarantees the linkage between the two systems. They will depend on the burden distribution among sectors, *i.e.* on the abatement realized within the domestic market compared to the international constraint. But the precise institutional arrangements that will prevail are unknown for the moment, so we make several assumptions about the design of the tax system, and study their consequences.

We study in section 2 the behavior of European entities trading on the European

2. European Directive 2003/87/CE, called "*Directive PEN*" published in the Official Journal of the European Union on October the 13th, 2003.

3. The six main greenhouse gases concerned by the Kyoto Protocol are carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFC_s), perfluorocarbons (PFC_s) and sulphur hexafluoride (SF₆), and expressed as equivalent CO₂.

market. We deduce the optimal level of abatement of each country, holding account of the constraints established in the different NAPs. Then, we deal with the consequences of a tax implementation on the behavior of non-covered European entities. We finally study, as a benchmark, the optimal solution, that is to say the initial allocations for covered sectors and the tax rates for non-covered sectors that a European central planner would implement in order to satisfy the Kyoto target at least cost. In section 3, we introduce the International Emissions Trading scheme and describe the behavior of participating countries. We consider three possible cases of linkage. In the first one, a European regulator is the representative actor on the international market; he is able to purchase or sell international permits to ensure the compliance and then he imposes to European countries the same tax rate on their non-covered sectors, equal to the international carbon price. In the second case, there is no European regulator and national governments neglect the possibilities of cost reduction offered by the international market. Then, they fix their own tax rate, to attain their Kyoto objective within the *European Burden Sharing Act*. Finally, in the third case, a European regulator acts on the international market only and delegates to the countries the task of fixing their tax rate in order to attain the required abatement rate. Section 4 provides numerical estimations of the consequences of the previous assumptions. Finally, we conclude (section 5) by emphasizing the consequences of the current environmental policies and putting forward extensions to the model.

2 Europe

We consider that EU-ETS works independently from IET, over the period 2008-2012. European countries are indexed by k , with $k = 1, \dots, n$. We assume that in a given European country k , firms belonging to covered sectors can trade permits not only with other covered firms of the same country k , but also with firms of another European country⁴. Each sector is composed of identical firms. Moreover, we assume that European sectors are not allowed to engage, for their compliance, units associated with IET, such as project-based mechanisms units (ERUs and/or CERs)⁵. This assumption seems to be reasonable, because, at the moment, the amount of CERs and ERUs used by European entities is still marginal.

2.1 Covered sectors: the EUropean Emissions Trading Scheme

The sectors participating to EU-ETS are indexed by $j = 1, \dots, N$. They are the same in all European countries (*cf.* Annex I of Directive PEN).

4. This assumption is a simplification of reality. In reality indeed, the modeling of intra-European trade requires to define rules about reporting and units conversion. To be consistent with the Kyoto Protocol, trade between European firms in different member-states implies adjustments of countries AAUs amounts (see Carlen, 2004).

5. Industrial trading sectors are allowed to use CERs or/and ERUs for their compliance through the “*Linking Directive*”, but importation of broad units are limited. ERUs are credits associated to mechanisms of Joint-Implementation and CERs are credits associated to Clean Development Mechanisms.

According to the different NAPs, each sector j in a given European country k receives an amount of permits \bar{e}_{kj} , where $\sum_{j=1}^N \bar{e}_{kj} = \bar{e}_k$ ⁶. A low \bar{e}_{kj} means of course that the constraint is stringent, because it represents the level of authorized emissions. The sum over the European countries of the national allocations \bar{e}_k represents the overall European objective: $\sum_{k=1}^n \bar{e}_k = \bar{e}_{ets}$.

It is worth emphasizing that the usual logic of emissions trading systems is reversed here: the European countries decide on their own initial endowment \bar{e}_k , and the addition of these decisions determines the overall constraint \bar{e}_{ets} . The incentive for each European country not to choose an initial allocation equal to its business-as-usual emissions comes from the threat of the European Commission not to approve its NAP (see the case of the French NAP in December 2006).

Let e_{kj}^0 be the business-as-usual (BAU) emissions of sector j in country k , *i.e.* emissions without any environmental policy. Total BAU emissions within EU-ETS for covered sectors are $\sum_{k=1}^n \sum_{j=1}^N e_{kj}^0 = e_{ets}^0$. Moreover, a_{kj} is the abatement of sector j in country k . The remaining emissions after abatement are $e_{kj}^0 - a_{kj}$.

The effort of abatement a_{kj} provided by a sector j induces a cost $C_{kj}(a_{kj})$. The abatement cost function is supposed twice differentiable and strictly convex: $C'_{kj}(a_{kj}) > 0$ and $C''_{kj}(a_{kj}) > 0$. Abatement cost functions can differ among sectors and across countries because levels of technology are different (Jacoby and Wing, 1999).

Each sector j has to buy (or can sell) European permits at a competitive price p_e to fill the gap between emissions after abatement and its quantified target.

Then, each covered sector j seeks to minimize its compliance costs, by determining the optimal level of abatement:

$$\min_{a_{kj}} C_{kj}(a_{kj}) + p_e [(e_{kj}^0 - a_{kj}) - \bar{e}_{kj}] \quad \forall j = 1, \dots, N \text{ and } \forall k = 1, \dots, n. \quad (1)$$

The first order condition yields

$$C'_{kj}(a_{kj}) = p_e \quad \forall j = 1, \dots, N \text{ and } \forall k = 1, \dots, n. \quad (2)$$

So, as it is well known, the marginal abatement costs are equalized in each sector of each country participating to the European market, and the common marginal abatement cost equals the price of permits.

The equilibrium on the European permits market states that the sum of effective emissions after abatement is equal to the emission cap:

$$\sum_{k=1}^n \sum_{j=1}^N (e_{kj}^0 - a_{kj}) = \bar{e}_{ets}. \quad (3)$$

It allows us to obtain the price of permits. It can also be written as follows:

$$\sum_{k=1}^n \sum_{j=1}^N a_{kj} = e_{ets}^0 - \bar{e}_{ets}. \quad (4)$$

6. The initial allocation is given to European sectors by *grandfathering*, *i.e.* without charge and in proportion of their past emissions and their growth expectations.

The right-hand side member of equation (4) is the effort in terms of emissions reduction performed by covered European sectors, and the left-hand side member is the total abatement realized within EU-ETS.

2.2 Non-covered sectors: taxation

We consider here polluting sectors which are not included in EU-ETS. Their greenhouse gas emissions are however involved for the international compliance within the Kyoto Protocol. So, we assume that each European government implements an additional environmental policy, here a tax on emissions, in order to satisfy the international objectives. These sectors are specifically transport, and others, such as agriculture, waste and housing-tertiary. They are mainly emitters of non-point source pollution, and for this reason can hardly be included in EU-ETS. This justifies the choice of taxation for regulating their emissions. The coexistence of a domestic and an international emissions trading schemes, *i.e.* of two environmental policy instruments, implies a distribution of the burden among sectors. If the effort realized within the domestic market by covered sectors is low, then obviously the tax rate imposed on non-covered European sectors will be high, in order to respect the commitments.

Non-covered sectors in each European country k are indexed by $h = 1, \dots, M$. τ_k denotes the tax rate on the emissions of these sectors. We assume a single tax rate on all non-covered sectors, in line with the usual implemented fiscal policies. It is exogenous for non-covered sectors, but will be determined by each government in order to comply with its international obligations.

The abatement of non-covered sectors in a given European country k is b_{kh} , with $\sum_h b_{kh} = b_k$, and the baseline emissions f_{kh}^0 , with $\sum_h f_{kh}^0 = f_k^0$. Emissions after abatement are then $(f_{kh}^0 - b_{kh})$. $D_{kh}(b_{kh})$ denotes the abatement cost function, supposed twice differentiable and convex: $D'_{kh}(b_{kh}) > 0$ and $D''_{kh}(b_{kh}) > 0$. Non-covered sectors seek to minimize their costs by choosing the level of abatement:

$$\min_{b_{kh}} D_{kh}(b_{kh}) + \tau_k(f_{kh}^0 - b_{kh}) \quad \forall h = 1, \dots, M \text{ and } \forall k = 1, \dots, n. \quad (5)$$

Writing the first order condition yields the usual equality between marginal abatement costs and the tax rate:

$$D'_{kh}(b_{kh}) = \tau_k \quad \forall h = 1, \dots, M \text{ and } \forall k = 1, \dots, n. \quad (6)$$

2.3 Benchmark: the optimal solution

We assume the existence of a European central planner who seeks to minimize the total abatement cost of the European Union, for a given Kyoto commitment \bar{e}_{Ek} for each European country k . We want to calculate the efficient global constraint that should be imposed on covered sectors, and the optimal carbon price. We assume that non-European countries express a given net demand of permits on the Kyoto market ε_i^K , exogenous from the point of view of the European central planner.

The abatement of a covered sector j in a European country k is by definition equal to the difference between its BAU emissions and the sum of its initial allocation of permits and its purchase (sell) of European permits, denoted ε_{kj} , with $\varepsilon_{kj} \gtrless 0$:

$$a_{kj} = e_{kj}^0 - (\bar{e}_{kj} + \varepsilon_{kj}). \quad (7)$$

The total abatement of covered sectors of country k is then:

$$\sum_j a_{kj} = \sum_j e_{kj}^0 - \sum_j \bar{e}_{kj} - \sum_j \varepsilon_{kj} = e_k^0 - \bar{e}_k - \sum_j \varepsilon_{kj}. \quad (8)$$

The abatement of non-covered sectors in a country k allows it to comply with its Kyoto commitment. For this, it is necessary that the total abatement of country k equals the difference between its BAU emissions and its Kyoto commitment \bar{e}_{Ek} augmented by its purchases of European permits and of Kyoto permits, denoted ε_k^K :

$$\sum_j a_{kj} + \sum_h b_{kh} = e_k^0 + f_k^0 - \left(\bar{e}_{Ek} + \sum_j \varepsilon_{kj} + \varepsilon_k^K \right). \quad (9)$$

Equations (8) and (9) allow us to obtain the abatement of non-covered sectors of country k :

$$\sum_h b_{kh} = f_k^0 + \bar{e}_k - (\bar{e}_{Ek} + \varepsilon_k^K). \quad (10)$$

The constraints that must hold are the following:

$$\sum_k \sum_j \varepsilon_{kj} = 0, \quad (11)$$

$$\sum_k \varepsilon_k^K + \varepsilon_i^K = 0, \quad (12)$$

meaning that the sum of net purchase of permits must be equal to zero on the European market and on the Kyoto market as well.

Efficiency requires the minimization of the total abatement cost:

$$\min_{\varepsilon_{kj}, \bar{e}_{kj}, \varepsilon_k^K} \sum_k \left(\sum_j C_{kj}(a_{kj}) + \sum_h D_{kh}(b_{kh}) \right), \quad (13)$$

with respect to constraints (11) and (12).

Let p_1 and p_2 be the shadow carbon prices on each market. The first order conditions of the European planner's program yield:

$$C'_{kj}(a_{kj}) = p_1 = D'_{kh}(b_{kh}) = p_2 \quad \forall k, j \text{ and } h. \quad (14)$$

The efficient solution then consists in a single carbon price ($p^* = p_1 = p_2$), and in the equality of the marginal abatement costs for all sectors across all European countries. It

is then possible to obtain the efficient global constraint \bar{e}_{ets}^* that should be imposed on covered sectors in order to satisfy these conditions, for any given net demand of Kyoto permits by non-European countries.

This solution will be used as a benchmark in the numerical exercises performed below, and we will in particular evaluate the departure of the actual initial allocations from the efficient ones.

The next section describes the IET scheme. The overall objective to respect is a European objective (a reduction of 8% compared to the level of emissions in 1990), which is then shared among European countries. The behavior of each European government on this market will provide the additional tax rate to be implemented.

3 The International Emissions Trading scheme

The IET scheme will run from 2008 to 2012 and is established on a country level: governments are responsible for their compliance. Annex B Parties will have to reduce by 5.2 % their average level of emissions (compared to the base year, 1990) over the period. Parties participating to the international permits market are able to trade AAUs to be in compliance.

We consider that each Party is price taker and that the international market is competitive. p denotes the price of international permits.

In addition, we assume that the IET scheme is represented by two agents considered as two zones: “Europe”, indexed by E , and the “Rest of the Parties”, indexed by i ⁷.

These two zones must respect an international “cap” \bar{e} . The free initial allocations of permits for each zone are \bar{e}_E and \bar{e}_i , with $\bar{e}_E + \bar{e}_i = \bar{e}$. Hence, \bar{e} corresponds to the global international objective of 5.2 % in average over the period 2008-2012.

3.1 The Rest of the Parties

Let e_i^0 denote the baseline emissions for the Rest of the Parties. Zone i has to fulfill its commitment \bar{e}_i by reducing its polluting emissions or trading on the market. Notice that for zone i , all polluting sectors stated in the Kyoto Protocol are included. There is no distinction among sectors. The abatement of zone i is a_i and the remaining emissions after abatement are $(e_i^0 - a_i)$.

As for other Parties, the activity of cleaning up is associated with a twice differentiable, increasing and convex abatement cost function $K_i(a_i)$, where $K_i' > 0$ and $K_i'' > 0$.

Zone i minimizes its compliance costs:

$$\min_{a_i} K_i(a_i) + p [(e_i^0 - a_i) - \bar{e}_i], \quad (15)$$

yielding as usual:

$$K_i'(a_i) = p. \quad (16)$$

⁷ Bulgaria, Canada, Japan, Liechtenstein, Norway, New-Zealand, Romania, Russian Federation and Switzerland compose the “Rest of the Parties”.

3.2 Europe

Europe as a whole must respect its overall objective \bar{e}_E , where the objective of each European country \bar{e}_{Ek} is set in the *European Burden Sharing Act*. The current institutional arrangements, and in particular the fact that Europe is considered as a single zone, seem to suggest that the European actor on the market of international permits will be a single European entity, that we name the European regulator. Nevertheless, we study here different *scenari* concerning the potential behavior of European countries on the international market, and compare their consequences. We assume that European constraints for covered sectors are given, while the tax rates imposed on non-covered sectors are still undetermined. Then, the tax rate must compensate the difference between European emissions of covered sectors and the international European objective.

3.2.1 European regulator able to impose the national tax rates

Suppose first that there exists a European regulator able to impose to European governments the tax rates they must apply to their non-covered sectors. Then, obviously, he will impose in each European country a tax rate on emissions of non-covered sectors equal to the price of an international permit⁸, given that this price reflects the global environmental constraint:

$$\tau_k = p \quad \forall k. \quad (17)$$

The abatement of non-covered sectors in a country k is then $b_{kh} = D'_{kh}{}^{-1}(p)$. Everything goes as if the non-covered sectors of all European countries were allowed to trade permits directly on the international market, and the equilibrium of the market is, in terms of abatements:

$$a_i + \sum_{k=1}^n \sum_{h=1}^M b_{kh} = (e^0 - \bar{e}) - (e_{\text{ets}}^0 - \bar{e}_{\text{ets}}). \quad (18)$$

The abatement of the Rest of the Parties and of the European non-covered sectors is equal to the difference between the global Kyoto effort $e^0 - \bar{e}$ and the effort realized by the European covered sectors $e_{\text{ets}}^0 - \bar{e}_{\text{ets}}$.

This solution is not very plausible. Fixing the tax rates is still a state prerogative, that will not be so easily given up to the European regulator, all the more so since the determination of the NAPs remains a domestic prerogative.

3.2.2 National regulators fixing their own tax rates

So let us consider now that each national regulator does not take into account opportunities provided by the international market. It implies that each European government determines its own tax rate τ_k , in order to reach its Kyoto target \bar{e}_{Ek} , the effort realized by the covered sectors being considered as given.

8. This simple static set-up prevents from taking into account the fact that a tax rate is fixed for a certain time length, while a market price varies daily. In a more general set-up, the tax rate should be a mean of the carbon market prices.

For European country k , the iso-abatement curve associated with the abatement objective $e_k^0 + f_k^0 - \bar{e}_{Ek}$ gives the relationship between the tax rate supported by the non-covered sectors and the level of the constraint imposed on covered sectors. It can be written as follows:

$$\sum_{j=1}^N a_{kj} + \sum_{h=1}^M b_{kh} = e_k^0 + f_k^0 - \bar{e}_{Ek}, \quad (19)$$

or, the abatement levels a_{kj} and b_{kh} being given by the first order conditions (2) and (6) and the price of European permits by equation (4):

$$\sum_{j=1}^N C'_{kj}{}^{-1}(p_e) + \sum_{h=1}^M D'_k{}^{-1}(\tau_k) = e_k^0 + f_k^0 - \bar{e}_{Ek}, \quad (20)$$

with

$$\sum_{k=1}^n \sum_{j=1}^N C'_{kj}{}^{-1}(p_e) = e_{\text{ets}}^0 - \bar{e}_{\text{ets}}. \quad (21)$$

We can see that the weight of the initial allocation \bar{e}_k of a given European country k in its iso-abatement curve is “diluted” in the global constraint \bar{e}_{ets} through the European market. Every country is then incited to propose to the European Commission a NAP assigning an effort to its covered sectors as small as possible, hoping that the others will do the job without enforcing it to increase the tax rate τ_k to meet a given abatement objective.

The obvious drawbacks of this solution is that Europe does not take advantage of the international market to reduce its abatement costs. Its merit is that each European country remains sovereign as far as its fiscal policy is concerned.

3.2.3 European regulator acting on the international market only

We suppose now that there exists a European regulator whose job is to determine jointly the total European rate of abatement and the net purchases of international permits, given the Kyoto constraint on European emissions \bar{e}_E .

Let e_E^0 denote the total European BAU emissions. They are the sum of the emissions of covered and non-covered sectors:

$$e_E^0 = \sum_{k=1}^n e_k^0 + \sum_{k=1}^n f_k^0 = e_{\text{ets}}^0 + \sum_{k=1}^n f_k^0. \quad (22)$$

To determine the total level of abatement, the European regulator minimizes its compliance costs. We suppose that he uses an aggregate abatement cost function for Europe $K(a_E)$. The relationship between the sectoral cost functions and this aggregate cost function is given in the Appendix. Thus, the program of cost minimization for the European regulator acting on the international market is written as follows:

$$\min_{a_E} K_E(a_E) + p[(e_E^0 - a_E) - \bar{e}_E], \quad (23)$$

and the first order condition yields:

$$K'_E(a_E) = p. \quad (24)$$

The competitive price of an international permit is given by the equilibrium on the market:

$$a_i + a_E = e^0 - \bar{e}, \quad (25)$$

where a_i and a_E are given by the first order conditions (16) and (24).

This total European abatement effort within the IET decided by the European regulator is also the sum of the abatement efforts of the n European countries:

$$a_E(p) = \sum_{k=1}^n \left(\sum_{j=1}^N a_{kj}(p_e) + \sum_{h=1}^M b_{kh}(\tau_k) \right), \quad (26)$$

where $a_E(p)$ is given by equation (24), $a_{kj}(p_e)$ by equation (2) and $b_k(\tau_k)$ by equation (6). As we assume that allocations for covered sectors are given, then each tax rate must be calculated in a way to satisfy equation (26). Obviously, a unique tax rates system solution of this equation does not exist. A constraint must be added, describing the sharing of efforts among the European countries, which could be proportional to their emissions reduction objective of the *European Burden Sharing Act*. We would then have

$$\frac{a_{Ek}(p_e, \tau_k)}{\bar{e}_{Ek}} = \frac{a_E(p)}{\bar{e}_E}, \quad (27)$$

which allows us to obtain τ_k knowing p_e and p .

4 Simulations

We simulate now the previous model, and determine for every European country the tax rate that should be implemented and the resulting abatement for covered and non-covered sectors.

4.1 The tax rates for quadratic abatement cost functions

The assumptions made for the characteristics of the abatement cost functions –convexity and degree of steepness– are very important. We consider a quadratic abatement cost function because it is convex, it yields linear marginal abatement costs, which greatly simplifies the simulations, and finally there is no convincing argument in the literature to do otherwise.

Sectoral abatement cost functions are then

$$C_{kj}(a_{kj}) = \frac{\alpha_{kj}}{2} a_{kj}^2, \quad (28)$$

$$D_{kh}(b_{kh}) = \frac{\beta_{kh}}{2} b_{kh}^2. \quad (29)$$

Parameters $\alpha_{kj} > 0$ and $\beta_{kh} > 0$ represent the levels of abatement technology, which differ between countries and between sectors. The more malleable the production process, the lower the parameter, and the lower the cost of reduction of pollution (Jacoby and Wing, 1999). Opportunities of substitution in the production process, i.e. substitution between polluting and clean inputs, are thought to be more important for covered sectors, in particular for energy.

We can deduce through the first order conditions (2) and (6) that

$$a_{kj} = p_e \frac{1}{\alpha_{kj}}, \quad (30)$$

$$b_{kh} = \tau_k \frac{1}{\beta_{kh}}, \quad (31)$$

and the equilibrium of the market for emission permits (4) yields:

$$p_e = \frac{e_{\text{ets}}^0 - \bar{e}_{\text{ets}}}{\sum_{k=1}^n \sum_{j=1}^N \frac{1}{\alpha_{kj}}}. \quad (32)$$

We can now calculate the tax rates on non-covered European sectors in the different cases studied above.

4.1.1 Benchmark

We must find the optimal carbon price and the initial global constraint \bar{e}_{ets}^* that lead to the equalization of all the marginal abatement costs, for covered and non-covered sectors, in every European country, given the international demand for permits ε_i^K and the Kyoto commitments \bar{e}_{Ek} .

The international demand of permits is of course related to the level of abatement of non-European countries:

$$\varepsilon_i^K = e_i^0 - a_i - \bar{e}_i. \quad (33)$$

Equation (9) reads:

$$p \left(\sum_j \frac{1}{\alpha_{kj}} + \sum_h \frac{1}{\beta_{kh}} \right) = e_k^0 + f_k^0 - \left(\bar{e}_{Ek} + \sum_j \varepsilon_{kj} + \varepsilon_k^K \right), \quad (34)$$

and the sum of these equations over all European countries combined to the equilibrium constraints and the preceding expression of ε_i^K gives:

$$p \sum_k \left(\sum_j \frac{1}{\alpha_{kj}} + \sum_h \frac{1}{\beta_{kh}} \right) = \sum_k (e_k^0 + f_k^0 - \bar{e}_{Ek}) + e_i^0 - \frac{p}{\gamma_i} - \bar{e}_i = e^0 - \bar{e} - \frac{p}{\gamma_i}. \quad (35)$$

The optimal carbon price is then:

$$p^* = \frac{e^0 - \bar{e}}{\frac{1}{\gamma_i} + \sum_k \left(\sum_j \frac{1}{\alpha_{kj}} + \sum_h \frac{1}{\beta_{kh}} \right)}. \quad (36)$$

This allows us to obtain the abatements $a_{kj}^* = p^*/\alpha_{kj}$, $b_{kh}^* = p^*/\beta_{kh}$, $a_i^* = p^*/\gamma_i$, as well as

$$(\bar{e}_{kj} + \varepsilon_{kj})^* = e_{kj}^0 - \frac{p^*}{\alpha_{kj}} \quad (37)$$

$$(\bar{e}_k - \varepsilon_k^K)^* = \bar{e}_{Ek} - f_k^0 + p^* \sum_h \frac{1}{\beta_{kh}}, \quad (38)$$

and, by summing over all sectors and all European countries,

$$\bar{e}_{ets}^* = e_{ets}^0 - p \sum_k \sum_j \frac{1}{\alpha_{kj}}. \quad (39)$$

Equation (39) gives the optimal total constraint on covered sectors within EU-ETS. Equation (38) shows that the optimal constraint for each European country is not determined uniquely: what is unique is the difference between this constraint and the net purchase of Kyoto permits by the country. It is the same at a sectoral level (equation (37)).

4.1.2 European regulator able to impose the national tax rates

We then have $b_{kh} = \frac{p}{\beta_{kh}}$, and equation (18) yields:

$$p = \tau_k = \frac{(e^0 - \bar{e}) - (e_{ets}^0 - \bar{e}_{ets})}{\frac{1}{\gamma_i} + \sum_k \sum_h \frac{1}{\beta_{kh}}}. \quad (40)$$

We can see easily that this carbon price is the same as the optimal one given by equation (36) if and only if the global constraint on the European market is such that

$$\frac{e_{ets}^0 - \bar{e}_{ets}}{\sum_k \sum_j \frac{1}{\alpha_{kj}}} = \frac{e^0 - \bar{e}}{\frac{1}{\gamma_i} + \sum_k \left(\sum_j \frac{1}{\alpha_{kj}} + \sum_h \frac{1}{\beta_{kh}} \right)}, \quad (41)$$

i.e. if the distribution of the efforts of abatement is the same in the European market and in the Kyoto market.

4.1.3 National regulators fixing their own tax rates

Then, equation (20) yields:

$$\tau_k = \frac{e_k^0 + f_k^0 - \bar{e}_{Ek} - (e_{ets}^0 - \bar{e}_{ets}) \frac{\sum_j \frac{1}{\alpha_{kj}}}{\sum_k \sum_j \frac{1}{\alpha_{kj}}}}{\sum_h \frac{1}{\beta_{kh}}}. \quad (42)$$

4.1.4 European regulator acting on the international market only

We show in the Appendix that the aggregate cost function for Europe is also quadratic, and can be written

$$K(a_E) = \frac{\gamma_E}{2} a_E^2, \quad (43)$$

with

$$\gamma_E = \frac{1}{\sum_k \left(\sum_j \frac{1}{\alpha_{kj}} + \sum_h \frac{1}{\beta_k} \right)}. \quad (44)$$

We can then easily deduce from equation (27) the tax rates in the quadratic case:

$$\tau_k = \frac{p \frac{1}{\gamma_E} \frac{\bar{e}_{Ek}}{\bar{e}_E} - p_e \sum_j \frac{1}{\alpha_{kj}}}{\sum_h \frac{1}{\beta_{kh}}}, \quad (45)$$

p being given by the equilibrium condition on the international permits market (equation (25)):

$$p = \frac{e^0 - \bar{e}}{\frac{1}{\gamma_i} + \frac{1}{\gamma_E}}, \quad (46)$$

which finally allows us to obtain

$$\tau_k = \frac{1}{\sum_h \frac{1}{\beta_{kh}}} \left(\frac{e^0 - \bar{e}}{\frac{1}{\gamma_i} + \frac{1}{\gamma_E}} \frac{1}{\gamma_E} \frac{\bar{e}_{Ek}}{\bar{e}_E} - \frac{e_{ets}^0 - \bar{e}_{ets}}{\sum_k \sum_j \frac{1}{\alpha_{kj}}} \sum_j \frac{1}{\alpha_{kj}} \right). \quad (47)$$

4.2 Simulations

4.2.1 The data

For European countries, the data used for the simulations come from the European Pollutant Emission Register⁹, from the estimated NAPs for 2008-2012 and finally from the data of the POLES model (Criqui *et al.*, 2003). We obtain BAU emissions for 2010, for all covered sectors, the allocations per year and also the environmental constraints. Moreover, we use BAU data for non-covered sectors and other countries participating to the international emissions trading scheme. We use specifically data from the national reports submitted to the UNFCCC¹⁰. European covered sectors are: energy activities (refining, other combustion activities), production and processing of ferrous metals, mineral industry (cement, glass, lime, ceramics products...) and chemical industry, pulp and paper production and manufacturing industries and construction.

We assume that there are two representative non-covered sectors. The first one is transport, and the second one includes agriculture, housing-tertiary, wastes and other industrial sectors not included in the preceding list. Table 1 gives total greenhouse gas emissions (in Mt CO₂ equivalent) for the base year 1990, as considered by the Kyoto Protocol, and Kyoto's targets for 2008-2012, for European countries and the Rest of the Parties.

9. <http://www.eper.cec.eu.int>

10. <http://www.unfccc.int>

Table 1. Greenhouse gas emissions (Mt eqCO₂) and international environmental target (%) under the Kyoto Protocol

	AUS	Baltic states	B.LUX	CZ REP	DNK	FIN	FRA	GER	GRC	HUN
Em. 1990	54.01	89.35	120.38	145.21	51.36	52.12	367.27	933.9	77.21	79.71
Target	-13	-8	-9	-8	-21	0	0	-21	25	-6
	IRE	ITA	NDL	POL	PRT	SLK	SMC	SPA	SWE	UK
Em. 1990	30.38	404.09	150.59	463	39.08	55.36	23.36	207.18	50.89	568.88
Target	13	-6.5	-6	-6	27	-8	-8	15	4	-12.5
	BUL	CAN	EU	JAP	LIE	NOR	N-Z	ROM	RUS FED	SWI
Em. 1990	157.09	607.19	3963.33	1246.73	0.21	51.96	73.16	163.6	2360	48.5
Target	-8	-6	-8	-6	-8	1	0	-8	0	-8

Source: UNFCCC.

4.2.2 Calibration

The most important point for our purpose is the calibration of the parameters of the marginal abatement cost functions. Unfortunately, estimates of marginal abatement costs vary widely in the literature. These estimates are usually obtained by simulation of a model, and the structural modeling choices greatly impact the results. Following the IPCC framework (Fischer and Morgenstern, 2006), four main factors contribute to variances in estimates: the projections of base case emissions, the structural characteristics of the model (sectoral and technical detail, optimization techniques, functional forms...), the climate policy regime considered and finally the consideration of adverted climate damages. After data on marginal abatement costs have been obtained by simulation, these data are fitted to a chosen specification of the abatement cost function, allowing to obtain the parameters of this function. Finally, we need here not only estimates of aggregate marginal abatement costs, but also sectoral data, more difficult to obtain.

This article uses estimates provided by the POLES model (Criqui *et al*, 2003). POLES is a bottom-up model, with elaborated data concerning different polluting sectors, specific levels of technology and recent projections of business-as-usual emissions. We consider here five main sectors covered by EU-ETS, which are chemistry, electricity, mineral industry, industry of ferrous metals and finally other industries such as pulp and paper. We use POLES to determine the technological parameters included in the abatement cost functions. More precisely, POLES calculates the level of emissions in 2012 in terms of spread (expressed as a percentage) compared to the constraint, for a carbon price ranging from 0 to 42 €. Thus, we calculate the parameters values through these estimated values

of emissions¹¹. Table 2 gives the results of the calibration.

Table 2. Estimated technological parameters

		Gbr	Fra	Ita	Ger	Esp	Grc	Prt	BLN	Swe	Pol	Hun	New count.	other count.
covered (α_{kj})	Chem.	2.51	0.67	2.46	0.29	0.78	61.19	6.56	1.78	27.72	0.93	34.86	27.72	46.27
	Steel	1.64	1.48	1.36	9.53	2.72	274.7	622.6	2.35	1.60	1.48	23.09	28.54	41.55
	NMM	51.89	12.27	4.16	9.53	2.21	7.06	3.08	53.06	96.15	27.89	166.4	328.8	115.6
	Other													
	in- dus.	0.31	0.44	0.24	0.12	0.38	0.95	1.69	3.49	1.51	1.31	10.38	11.35	3.50
	Elec.	0.09	0.21	0.12	0.05	0.10	0.35	0.71	0.41	3.63	0.13	1.51	1.46	0.75
non- covered (β_{kh})	Trans.	0.11	0.11	0.15	0.11	0.11	0.59	0.51	0.39	0.72	0.93	1.27	2.86	1.08
	Others	0.20	0.20	0.24	0.17	0.41	1.12	2.45	0.62	8.39	0.75	2.13	9.01	3.01

Source: POLES model and own calculations.

BLN : Belgium, Luxembourg, Netherlands.

New countries : Baltic States, Czech Republic, Cyprus, Malta, Slovakia, Slovenia.

Other countries: Austria, Denmark, Finland, Ireland.

Our assumption of linear marginal costs is clearly very rough: all the differences among sectors and across countries in terms of technologies, possibilities of substitution between dirty and clean inputs, efforts already done to adopt cleaner production processes... are embodied in a single parameter. For instance, a high value of the parameter of the marginal abatement cost suggests that the opportunities of substitution are low. This can be due either to the fact that some sectors or some countries have already done important efforts by developing cleaner technologies (electricity sector in Sweden for instance), or to the fact that some others do not have any available clean processes of production.

4.2.3 The tax rates and abatements

We present now the results of the different simulations. They are very sensitive to the value of the parameter γ_i , the level of technology used in the cost abatement function for zone “Rest of the Parties”. In the absence of information which could have helped us to make a better choice, we suppose here that γ_i is equal to the calibrated value of γ_e .

The exogenous variables are given in tables 3 and 4. Their values result from the data of the United Nations Framework Convention on Climate Change (figures reported in national submissions) and from POLES data (concerning baseline emissions of covered sectors).

¹¹. We calculate parameters on estimated values because so far there is no data about the abatement realized through the carbon market for European countries, this instrument being too recent.

Table 3. Exogenous variables (Mt eqCO₂)

e_{ets}^0	\bar{e}_{ets}	\bar{e}_E	e_E^0	\bar{e}_i	e_i^0	e^0	\bar{e}	γ_i
2339.7	2083.6	3645.9	4944.6	4568.2	4667.4	9612.02	8214	0.005

Source: UNFCCC and POLES.

Table 4. Initial allocations to covered sectors (\bar{e}_{kj})

	Gbr	Fra	Ita	Ger	Esp	Grc	Prt	BLN	Swe	Pol	Hun	New count.	other count.
Chem.	10.1	13.2	10.4	6.2	6.5	0.8	1.0	23.3	2.0	7.9	3.5	7.6	2.2
Steel	19.9	27.5	23.3	37.4	9.7	1.5	0.4	24.0	8.1	18.6	3.4	29.3	15.9
NMM	17.2	21.8	37.4	51.2	33.1	12.5	8.6	15.3	5.2	19.9	5.0	19.0	14.0
Oth. ind.	8.9	19.6	4.8	3.4	4.4	1.3	0.3	11.9	2.3	11.7	0.3	4.6	7.4
Elec.	167.7	62.1	127.1	358.8	93.2	54.4	24.8	69.4	6.9	216.8	23.6	150.0	74.9
total	223.7	144.2	203.0	456.9	146.9	70.3	35.1	144.0	24.5	274.9	35.9	210.5	114.4

Source: POLES.

Table 5 gives the results of the benchmark simulation. We calculate the single carbon price ($p^* = 3.5 \text{ €/teq CO}_2$), and the optimal global constraint on European covered sectors ($\bar{e}_{ets}^* = 1895.5 \text{ Mt eqCO}_2$). Notice that this constraint is about 10% lower than the actual one ($\bar{e}_{ets} = 2083.6 \text{ Mt eqCO}_2$), which supports the analysis of many observers stressing that the allocations within EU-ETS are too lenient (see for instance Godard 2005). We then deduce the levels of abatement for each sector in each European country and for the “Rest of the Parties”. The abatements are reported as a percentage of BAU emissions, to have a measure of the efforts demanded to the different sectors in the different countries.

Marginal costs of abatement are equalized in the benchmark. Nevertheless, the results show that non-covered sectors and especially transport would have to assume an important part of the burden. As for covered sectors, electricity would have to fulfill the main part of the commitment. At a country level, Sweden, which is well-known as an environmentally friendly country, would have to do a low effort to reach its target, except in the steel sector, compared to France, Germany or United Kingdom. Moreover, the generous Kyoto targets in Eastern Europe countries (“hot air”) introduce variances between levels of abatement among countries. Finally, we calculate the abatement for zone “Rest of the Parties”: $a_i = 699.10 \text{ Mt eqCO}_2$, that is to say 16% of BAU emissions.

We now examine the three potential cases of linkages, focusing on the discrepancy of abatement levels, tax rates and permit prices. Notice that from now on, the national European constraints are determined *ex ante*. Table 6 reports the abatement efforts of

Table 5. Abatement efforts in the benchmark case (% of BAU emissions), $p^* = 3.5 \text{ €/teq CO}_2$

		Gbr	Fra	Ita	Ger	Esp	Grc	Prt	BLN	Swe	Pol	Hun	New count.	other count.
covered (a_{kj}^*)	Chem.	10.1	24.1	10.6	44.4	35.8	8.1	23.8	16.7	13.0	26.9	5.9	32.8	19.3
	Steel	11.6	15.3	14.3	0.9	16.3	7.5	4.7	16.6	57.5	12.2	5.3	6.8	23.8
	NMM	1.7	3.5	5.6	2.7	9.8	10.1	17.6	3.8	3.2	2.7	2.0	2.8	8.8
	Oth. ind.	30.8	28.0	57.5	92.5	46.1	68.4	45.5	20.4	33.3	18.6	15.2	50.7	23.7
	Elec.	15.3	18.7	18.4	15.0	25.3	17.7	21.7	19.0	11.5	12.2	10.8	14.4	20.0
non- covered (b_{kh}^*)	Trans.	20.6	20.8	19.3	18.1	29.5	25.0	33.7	24.9	20.8	14.6	24.2	26.9	26.4
	Others	4.7	7.2	10.5	6.0	5.8	8.1	5.0	13.4	2.5	3.4	4.2	2.7	5.1

European covered sectors within EU-ETS. The European carbon price is $p_e = 2 \text{ €/teq CO}_2$. It is much lower than the benchmark carbon price ($p^* = 3.5 \text{ €/teq CO}_2$). Then, obviously, the carbon prices for non-covered sectors will be higher, whatever the behavior of the European regulator.

Table 6. Abatement efforts of covered sectors within EU-ETS (% of BAU emissions), $p_e = 2 \text{ €/teq CO}_2$

	Gbr	Fra	Ita	Ger	Esp	Grc	Prt	BLN	Swe	Pol	Hun	New count.	other count.
Chem.	5.8	13.9	6.1	25.6	20.7	4.6	13.7	9.7	7.5	15.5	3.4	18.9	11.1
Steel	6.7	8.8	8.3	0.5	9.4	4.3	2.7	9.6	33.2	7.1	3.1	3.9	13.7
NMM	1.0	2.0	3.2	1.6	5.6	5.9	10.2	2.2	1.8	1.5	1.2	1.6	5.1
Oth. ind.	17.8	16.1	33.2	53.3	26.6	39.4	26.3	11.8	19.2	10.7	8.8	29.2	13.7
Elec.	8.8	10.8	10.6	8.7	14.6	10.2	12.5	11.0	6.7	7.1	6.2	8.3	11.5

Table 7 reports the abatement efforts of European non-covered sectors in the case where there exist a European regulator able to impose the national tax rates. Remember that in this case, everything goes as if the non-covered sectors were allowed to act on the international market. The tax rates are equal to the international permit price, $p = 4.1 \text{ €/teq CO}_2$. The carbon price is then higher for non-covered sectors than for covered ones.

We observe a great variance in the required levels of abatements for non-covered sectors. Transport generally supports the main part of the burden.

The fact that the international permit price is higher than the optimal one induces a

higher effort demanded to the “Rest of the Parties”: $a_i = 802.2$ Mt eqCO₂, reflecting a reduction by 19% of BAU emissions.

Table 7. Abatement efforts of non-covered sectors (% of BAU emissions) in the case where the European regulator is able to impose the national tax rates, $p = 4.1$ €/teq CO₂

	Gbr	Fra	Ita	Ger	Esp	Grc	Prt	BLN	Swe	Pol	Hun	New count.	other count.
Trans.	24.1	24.4	22.6	21.3	34.6	29.3	39.4	29.4	24.4	17.1	28.3	31.5	30.9
Others	5.5	8.4	12.3	7.1	6.8	9.5	5.9	15.8	3.0	4.0	4.9	3.1	6.0

We study now the situation where national European regulators do not take into account the international system. We find the different tax rates imposed on non-covered sectors (table 8).

Table 8. Tax rates and abatement efforts (% of BAU emissions) in the case where national regulators fix their own tax rate

	Gbr	Fra	Ita	Ger	Esp	Grc	Prt	BLN	Swe	Pol	Hun	New count.	other count.
τ_k	21.7	13.1	7.7	17.6	15.5	10.1	13.1	6.5	2.7	0.0	1.9	5.7	18.6
Trans.	127.7	77.7	42.7	91.2	130.3	72.5	46.6	43.1	16.1	0.0	12.8	46.8	128.1
Others	29.3	26.8	23.3	30.4	25.7	23.6	25.1	20.9	2.0	0.0	2.2	4.6	24.6

The main result here is that the tax rates are in general much higher than the European permit price paid by covered sectors, but also much higher than the unique tax rate of the previous simulation. It means that when countries do not take into account the opportunities provided by the international market they transfer a huge part of the burden to non-covered sectors. Acting on the international market enables entities to share the effort through trade. This case is then characterized by great distortions among sectors. Tax rates greater than 100% occur for transport in Great Britain and Spain, meaning that these sectors must reduce their emissions to zero, which can only be achieved by a complete change of technology. Moreover, the global effort is not fairly allocated among countries. Eastern European countries are required to do a relatively low effort, because of their low Kyoto constraint. Poland for instance can achieve its Kyoto commitment without implementing any additional environmental policy. On the contrary, the high levels of tax rates suggest that the “old European countries” should make an important

additional effort to ensure compliance. The case of Spain is interesting and underlines the fact that EU-ETS allocations are sometimes not adapted: actually, the tax rate to impose is high, while this country has an international objective of reduction which is positive (+15% compared to 1990). It means that expected BAU emissions will widely exceed the Kyoto constraint.

To conclude, this case of linkage seems to be the less desirable. Indeed, to reach the same target, non-covered European sectors would have to support very high tax rates, which would intensify sectoral distortions.

Finally, we study the case where the European regulator acts on the international market. We still deduce the different tax rates, the levels of abatement for covered sectors, non-covered sectors and for the Rest of the Parties and a new international permit price (table 9).

Table 9. Taxation and abatement efforts of non-covered sectors (% of BAU emissions) when a European regulator acts on the international market, $p = 3, 5 \text{ €/teqCO}_2$

	Gbr	Fra	Ita	Ger	Esp	Grc	Prt	BLN	Swe	Pol	Hun	New count.	other count.
τ_k	5,6	4,3	4,8	6,1	1,9	4,6	2,3	4,3	5,4	29,3	11,5	20,3	4,1
Trans.	32,7	25,5	26,4	31,8	16,1	32,8	21,6	29,4	32,0	122,7	79,1	95,2	26,5
Others	7,5	8,8	14,4	10,6	3,2	10,7	3,2	16,1	3,9	28,4	13,6	10,7	5,4

Notice that the international permit price is the same as in the benchmark situation, while the European permit price for covered sectors is lower. The tax rates imposed on non-covered sectors are in average higher than both the European and the international permit price. Despite trade between the “Rest of the Parties” and the European non-covered sectors, the burden on European non-covered sectors is still large. This is merely induced by too lenient European allocations. The main qualitative difference between this case and the previous one is the effort demanded to the non-covered sectors of the Eastern European countries. As this effort is nil or very low in the previous case, it is high here, because the mechanism of allocation of the effort does not allow them to take advantage of the hot air. On a global level, the European regulator may shift the environmental burden on the less technologically advanced countries, in order to stimulate technological innovation.

5 Concluding remarks

To fulfill their international commitments, European governments will have to implement a tax rate on initially non-covered sectors. The main message of the paper is that if

the allocations granted to covered sectors continue to be globally too lenient, the burden imposed on non-covered sectors (among which transport mainly) and the distortions between sectors and countries will be important. Moreover, the precise way of determining the tax rates will have a great impact. It is essential to take advantage of the international market, which allows to alleviate through trade the burden on non-covered sectors.

The first important extension of the model would be the introduction of project mechanisms (Clean Development Mechanisms and Joint Implementation). These opportunities are not yet used extensively, but they will in the future be the clue of the consistent coexistence of the two systems.

Another interesting extension would be to abandon the assumption of a competitive international market, and to introduce a possible market power of the European Union or of some Parties, such as Russia which benefits from “hot air”.

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Appendix: the aggregate abatement cost function

We define the aggregate abatement cost function for any abatement a as the minimum of the sum of the sectoral abatement costs functions for all European countries, given that the sum of sectoral abatements is equal to the aggregate abatement (see for instance Bréchet and Michel, 2005):

$$K_E(a) = \begin{cases} \min \sum_k \left(\sum_j C_{kj}(a_{kj}) + \sum_h D_{kh}(b_{kh}) \right) \\ a = \sum_k \left(\sum_j a_{kj} + \sum_h b_{kh} \right). \end{cases}$$

The Lagrangian of this program is:

$$\mathcal{L} = \sum_k \left(\sum_j C_{kj}(a_{kj}) + \sum_h D_{kh}(b_{kh}) \right) + \lambda \left[a - \sum_k \left(\sum_{j=1}^N a_{kj} + \sum_h b_{kh} \right) \right],$$

and the first order conditions yield:

$$\lambda = C'_{kj}(a_{kj}) = D'_{kh}(b_{kh}).$$

We then obtain the sectoral abatements as functions of the Lagrange multiplier λ :

$$\begin{aligned} \hat{a}_{kj} &= C'_{kj}{}^{-1}(\lambda) \\ \hat{b}_{kh} &= D'_{kh}{}^{-1}(\lambda) \\ \hat{a} &= \sum_k \left(\sum_j C'_{kj}{}^{-1}(\lambda) + \sum_h D'_{kh}{}^{-1}(\lambda) \right). \end{aligned}$$

If the sectoral abatement cost functions are homogeneous of any given degree (let's say of degree $q \geq 1$ for exposition), the marginal cost functions are homogeneous of degree $q - 1$, and their inverse of degree $\frac{1}{q-1}$. We then have:

$$\hat{a} = \lambda^{\frac{1}{q-1}} \sum_k \left(\sum_j C'_{kj}{}^{-1}(1) + \sum_h D'_{kh}{}^{-1}(1) \right),$$

hence

$$\lambda = \left[\frac{\hat{a}}{\sum_k \left(\sum_j C'_{kj}{}^{-1}(1) + \sum_h D'_{kh}{}^{-1}(1) \right)} \right]^{q-1},$$

and

$$\begin{aligned} K_E(\hat{a}) &= \lambda^{\frac{q}{q-1}} \sum_k \left(\sum_j C_{kj}(C'_{kj}{}^{-1}(1)) + \sum_h D_{kh}(D'_{kh}{}^{-1}(1)) \right) \\ &= \hat{a}^q \frac{\sum_k \left(\sum_j C_{kj}(C'_{kj}{}^{-1}(1)) + \sum_h D_{kh}(D'_{kh}{}^{-1}(1)) \right)}{\left[\sum_k \left(\sum_j C'_{kj}{}^{-1}(1) + \sum_h D'_{kh}{}^{-1}(1) \right) \right]^q}. \end{aligned}$$

In the case of quadratic cost functions ($q = 2$), this can be simply written as:

$$\begin{aligned}
 K_E(\hat{a}) &= \hat{a}^2 \frac{\sum_k \left(\sum_j \frac{1}{2} \frac{\alpha_{kj}}{(\alpha_{kj})^2} + \sum_h \frac{1}{2} \frac{\beta_{kh}}{(\beta_{kh})^2} \right)}{\left[\sum_k \left(\sum_j \frac{1}{\alpha_{kj}} + \sum_h \frac{1}{\beta_{kh}} \right) \right]^2} \\
 &= \frac{1}{2} \frac{\hat{a}^2}{\sum_k \left(\sum_j \frac{1}{\alpha_{kj}} + \sum_h \frac{1}{\beta_{kh}} \right)} \\
 &= \frac{\gamma_E \hat{a}^2}{2},
 \end{aligned}$$

with

$$\gamma_E = \frac{1}{\sum_k \left(\sum_j \frac{1}{\alpha_{kj}} + \sum_h \frac{1}{\beta_{kh}} \right)}.$$

The aggregate cost function is quadratic, and its coefficient can be easily deduced from the coefficients of the sectoral cost functions.