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THE COMPETITIVENESS IMPACT OF CO2 EMISSIONS REDUCTION IN THE CEMENT SECTOR

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FOREWORD

This report was prepared by Damien Demailly and Philippe Quirion of the research institute CIRED, France, for the Joint Meetings of Tax and Environment Experts under the Committee on Fiscal Affairs and the Environment Policy Committee of OECD.

The work has benefited from a deep collaboration with the Institute for Prospective Technological Studies (IPTS – Joint Research Centre – European Commission). The analysis of competitiveness impacts of carbon mitigation policies on the cement industry is based on the world cement model CEMSIM developed by Dr. Laszlo Szabo, Ignacio Hidalgo, Juan Carlos Ciscar, Antonio Soria and Peter Russ, from the Energy group of the Sustainability in Industry, Energy and Transport (SIET) unit of the IPTS. For further details on their work, see [Szabo *et al.*, 2003; Szabo *et al.*, 2006] or visit www.jrc.es. The authors thank all these people and the IPTS for:

- The explanations on the model concepts, equations and architecture provided during the all study,
- The free access to a world cement industry database compatible with the model structure. The harmonisation and reformatting of this database required a labour-intensive activity. Built on commercially available information, the costs of this database were entirely borne by IPTS,
- Having hosted a CIRED member at the IPTS for two months.

Moreover, the development by the CIRED of the model GEO benefited from Lloyd's information put at the disposal of the CIRED by the IPTS. The authors also thank:

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THE COMPETITIVENESS IMPACT OF CO₂ EMISSIONS REDUCTION IN THE CEMENT SECTOR

EXECUTIVE SUMMARY

The cement sector is a large emitter of greenhouse gases

The cement consumption growth over the last decades, the high energy consumption and the very high carbon emissions make the cement sector an important greenhouse gas emitter. In the same time, the cement sector is potentially one of the most impacted by a climate policy: among twelve EU 15 industry sectors, non-metallic minerals – mostly cement – have the second direct CO₂ emission/turnover ratio. Cement manufacturers thus claim that an ambitious climate policy would impose an additional burden that may jeopardise their competitiveness and induce carbon leakage.

Indeed, given the last evolutions of the debate on GHG mitigation, it is clear today that regional rather than global policies will be implemented, at least for a while. Therefore, a distortion of competition may affect countries mitigating GHG emissions through the additional burden of tax policies, emission allowances... Such an asymmetric carbon constraint may of course have an impact on GHG-intensive industries competitiveness (loss of profitability and decreasing market shares, ultimately leading to relocation). Eventually, such fragmented policies might even be inefficient from an environmental point of view, if they generate relocations in countries that are more GHG-intensive because of their technological portfolio and their lack of environmental regulation. The competitiveness impact and the so-called “carbon leakage” due to this distortion is an argument against non global mitigation policy or at least in favour of compensations. That is why the measure of these effects is a priority in the discussion on GHG policies implementation.

There has so far been little empirical evidence that existing environmental regulations affect trade flows

Unfortunately, the existing economic literature has not been able to bring the debate to an end, possibly because of certain limitations of existing analyses. Ex post studies show very little empirical evidence that existing environmental regulations affect trade flows. However, in some CO₂ intensive sectors, the climate agenda may generate much higher environmental constraints than existing ones, hence the need for modelling such policies. The problem has thus been analyzed using both top-down and bottom-up models. One of the key points to assess competitiveness and carbon leakage impacts of GHG mitigation policies is the representation of international trade. In this regard, most models are based on the well-known Armington specification or on similar functional forms.

This specification assumes that the products are differentiated by their place of production. For example the chemicals produced by different countries are not perfect substitutes. This imperfect substitution has various grounds: products are not homogeneous throughout the world, consumers have national preferences, trade policies and transportation costs constitute barriers to trade. In the way most of the models use the Armington specification, all these obstacles to perfect substitution are merged in the Armington substitution elasticity, or a parameter with an equivalent meaning,

which is at best econometrically calibrated. Then, the market shares of the different producing countries are driven by relative prices and by this parameter.

However, for a product like cement, this could to some extent be an artefact of the modelling methods used

The Armington or Armington-like trade representation is widely used for two reasons. Firstly, it is convenient to avoid the "bang-bang effect", *i.e.* the fact that a small variation in relative prices can lead to drastic variations in market shares. Secondly, it is able to account for bilateral trade between two countries, which occurs in reality. However, this comes at the price of a lack of transparency and of control, since all the factors justifying the imperfect substitutability are merged. Furthermore, the econometric estimation of the Armington elasticity is difficult. Although this representation is probably the best compromise for most sectors, especially when aggregated, it proves to be rather debatable for some products like cement.

Cement is a relatively homogeneous product throughout the world, whose trade is not much disrupted by trade policies or national preferences. Transportation costs and capacity constraints are central to explain international trade patterns. Therefore, it is worth dealing with these factors more explicitly than in the conventional Armington-based models. In this aim, we developed the international trade model GEO that:

- Drops the imperfect substitution assumption among goods produced in different places;
- Makes explicit the transportation costs, for both road and sea transportation, utilising a spatial representation of the world;
- Represents the competition among producers in every consumption area, taking into account differentiated marginal production costs and transportation costs;
- Computes for every country a capacity constraint, which is not fixed but may be relaxed every year by investing in new capacities.

Several simulations have been done for this report on a new model system

To represent the cement industry, we use a modified version of CEMSIM, a recursive bottom-up model built by the IPTS team. The demand side of the model is based on a commodity intensity curve and a price-elastic demand, while the supply part features seven production technologies, fuel switch, material switch and retrofitting. GEO and CEMSIM are merged, allowing us to build a business-as-usual scenario until 2030 and three climate policy scenarios:

- A CO₂ tax or an Emission Trading Scheme (ETS) with auctioned allowances is implemented in the Kyoto Protocol Annex B countries that have ratified it, thereafter labelled "Annex B", assuming a CO₂ price of 15 euros per tonne;
- The same policy is implemented with Border-Tax Adjustments (BTA), *i.e.* a rebate on cement exports and a taxation of imported cement, is implemented. In the "Complete BTA" scenario, exported production is completely exempted from the climate policy and imports of cement from the rest of the world are taxed in accordance with the CO₂ intensity of the cement production in the exporting country. In the "WTO BTA" scenario, exports benefit from a rebate corresponding only to the least CO₂ intensive technology available at a large scale, and imports are taxed to the same level. Such a scenario would be compatible with the WTO rules, contrary to the first one we test.

Important increase in cement production is foreseen in the business-as-usual scenario

The business-as-usual (BaU) scenario generated by the CEMSIM-GEO model forecasts an important increase in cement production (2%/yr in average until 2030), entailing an alarming rise in CO₂ emissions (1.5%/yr). The CO₂

efficiency thus rises by 0.5%/yr, thanks to a more intensive use of waste and wood fuels and to the increasing share of modern machines and more energy-efficient technologies.

A CO₂ tax in Annex B countries would significantly reduce CO₂ emissions

The implementation of CO₂ tax or ETS in Annex B entails a significant decrease in CO₂ emissions in these countries (around 20%), through a more retrofitting toward energy-efficient technologies, a decrease in the rate of clinker (the CO₂ intensive input) in cement, a quicker switch to low carbon fuels (gas, waste and wood fuels) and a decrease in cement consumption. The impact on cement production in these countries is significant (-7.5% in 2010) because of both a cut in their domestic consumption level and a loss in competitiveness. For the latter reason, production and thus emissions in the rest of the world increase. The corresponding leakage rate is around 25% in 2010 (around 15% after), in the upper range of leakage estimates presented in the IPCC third assessment report (5 to 20%, cf. [Hourcade and Shukla, 2001]).

We stress that the policy tested in this report differs widely from the European emission trading scheme implemented since January 2005, because we model a tax or auctioned allowances whereas in the latter policy, emissions allowances are distributed freely to emitters in a regularly updated quantity. In the EU ETS, in most Member States, if an installation is closed, its operator will not receive allowances any more. Conversely, allowances will be issued for free to new installations. At last, the production level (and possibly the emissions level) will be taken into account in the quantity allocated in the next 5-years periods [Schleich and Betz, 2005]. It means that the incentive to reduce both emissions and cement production will be lower than modelled here. As a consequence, our results should not be interpreted as a prediction of what would happen should the European ETS be implemented in Europe and in the rest of the Kyoto Protocol Annex B.

The use of Border Tax Adjustments could limit production reductions in Annex B countries

Under the Complete BTA, the loss in production of Annex B countries is limited to 2% and the leakage is replaced by a spillover since emissions in the rest of the world decrease. The decrease in world emissions is a bit higher than without BTA. However, compared to BaU, non Annex B price competitiveness decreases a little and they lose some market shares, so these countries could claim that this system distorts competition in favour of Annex B countries. The WTO BTA cannot be criticised on this ground. It turns out to prevent leakage efficiently, the leakage rate being around 4% in 2010. The only drawback is that the WTO BTA, as the Complete BTA, leads to a higher increase in cement price and thus hurts more consumers in Annex B countries.

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INTRODUCTION

1. The cement consumption growth over the last decades, the high energy consumption and the very high carbon emissions, from fuel combustion and from the process itself, make the cement sector an important greenhouse gas emitter. The sector's emissions from fuel combustion represented 2.4% of the global carbon emissions in 1994 [IEA, 1999]. Adding process emissions, the sector reaches about 5% of the global anthropogenic CO₂ emissions. In the same time, the cement sector is potentially one of the most impacted by a climate policy: among twelve EU 15 industry sectors, non-metallic minerals – mostly cement – have the second direct CO₂ emission/turnover ratio [Quirion and Hourcade, 2004]¹. Cement manufacturers thus claim that an ambitious climate policy would impose an additional burden that may jeopardise their competitiveness and induce carbon leakage (cf. *e.g.* [British Cement Association, 2004]).

2. Indeed, given the last evolutions of the debate on GHG mitigation, it is clear today that regional rather than global policies will be implemented, at least for a while. Therefore, a distortion of competition may affect countries mitigating GHG emissions through the additional burden of tax policies, emission allowances... Such an asymmetric carbon constraint may of course have an impact on GHG-intensive industries competitiveness (loss of profitability and decreasing market shares, ultimately leading to relocation). Eventually, such fragmented policies might even be inefficient from an environmental point of view, if they generate relocations in countries that are more GHG-intensive because of their technological portfolio and their lack of environmental regulation. The competitiveness impact and the so-called “carbon leakage” due to this distortion is an argument against non global mitigation policy or at least in favour of compensations. That is why the measure of these effects is a priority in the discussion on GHG policies implementation.

3. Unfortunately, the existing economic literature has not been able to bring the debate to an end, possibly because of certain limitations of existing analyses.

4. In numerous *ex post* studies, economists have found little empirical evidence that existing environmental regulations affect trade flows (cf. *e.g.* [Raspiller and Riedinger, 2004]), and reference therein). One of the reasons would be that for most industries pollution abatement costs (or pollution emission costs) are a small component of total costs. Another possible reason is that industries with the largest pollution abatement costs happen to be the ones with high transportation costs that prevent production from locating far from customers [Ederington, 2003]. However, in some carbon intensive sectors like the cement industry the climate agenda may generate much higher environmental constraints than existing ones, hence the need for modelling such policies.

5. Beyond *ex post* studies, the problem has thus been analyzed using both top-down and bottom-up models. The key point to assess competitiveness and carbon leakage impacts of GHG mitigation policies is the representation of international trade.

¹ Only electricity generation has a higher ratio, but this sector is largely sheltered from international competition by transmission losses.

6. In this regard most models are based on the well-known Armington specification which assumes that products are not only distinguished by their kind but also by their place of production [Armington, 1969]. In other words, goods of the same kind produced by different countries are not perfect substitutes. This imperfect substitution has various grounds: products are not homogeneous throughout the world, consumers have national preferences, trade policies and transportation costs constitute barriers to trade. In the way most of the models use the Armington specification, all these obstacles to perfect substitution are merged in the Armington substitution elasticity, or a parameter with an equivalent meaning, which is at best econometrically calibrated. Then, the market shares of the different producing countries are driven by relative prices and by this parameter.

7. The Armington or Armington-like trade representation is widely used for two reasons. Firstly, it is convenient to avoid the "bang-bang effect", *i.e.* the fact that a small variation in relative prices can lead to drastic variations in market shares. Secondly, it is able to account for bilateral trade between two countries, which occurs in reality. However, this comes at the price of a lack of transparency and of control, since, in the way most models use it, all the factors justifying the imperfect substitutability are merged. Furthermore, the econometric estimation of the Armington elasticity is difficult².

8. Although this representation is probably the best compromise for aggregated markets and for most sectors, especially for high-technology products, it proves to be rather debatable, in the way most models use it, for the representation of a one good market like cement. Cement is a relatively homogeneous product throughout the world, whose trade is not much disrupted by trade policies or national preferences. The imperfect substitutability among cements from different places of production is then justified by the existence of very high transportation costs³. However, representing these transportation costs by a constant elasticity of substitution is a very crude assumption, especially if a single elasticity is chosen for every pair of countries, which is the case in most, if not all, applied models⁴.

9. A second limitation of most existing models is that they generally do not take into account explicitly production capacity shortages, whereas this issue is central to explain cement international trade patterns. This limitation could notably lead to overestimated leakage rates.

10. Thus, there is room for improving the representation of international trade in models addressing the competitiveness and leakage issues, especially for products like cement. We developed a spatial international trade model, GEO, that:

² Standard methods are likely to underestimate this coefficient [Erkel and Mirza, 2002]. For example, if an exporting country increases the quality of its products vis-à-vis its competitors (in other words if its non-price competitiveness is improved), it will typically increase both its export level and its price. If econometric estimations are not able to control this quality effect, they will wrongly find a positive correlation between the export price and quantity exported (or at least the observed correlation will be "less negative" than if quality was taken into account). As a consequence, export elasticities (*i.e.*, the decrease in exports following an increase in export price) will be underestimated, and Armington elasticities as well. However alternative econometric methods do not lead to robust results [Erkel and Mirza, 2002].

³ Whereas average cement price in Europe was around 70€ per tonne of cement in 2004, the sea transportation cost of a tonne of cement between Greece and Spain was around 22€, and the road transportation cost in France around 8€ per tonne and for 100km (transportation costs data supplied by LAFARGE). Therefore, cement generally does not travel more than 200km by road between the plant and the consumer. [ATILH, 2005]

⁴ In some models, transportation costs between countries are taken into account in prices, using a fixed transportation cost or real distances between national capitals. However, the countries are still treated as dimensionless point.

- Drops the imperfect substitution assumption among goods produced in different places;
- Makes explicit the transportation costs, for both road and sea transportation, utilising a spatial representation of the world: 47 producing countries and about 15 500 consuming areas are identified and geo-referenced, allowing to compute a realistic transportation cost for every (producing country – consuming area) pair;
- Represents the competition among producers in every consumption area, taking into account differentiated marginal production costs and transportation costs;
- Computes for every country a capacity constraint, which is not fixed but may be relaxed every year by investing in new capacities. GEOcp, a modified version of GEO, is used to estimate the construction of new capacities, which occurs when the average cost of the new plant (including its fixed, variable and transportation costs) does not prevent it to be more competitive in at least one market than the existing available capacities (if any) of other producers.

11. To represent the cement industry, we use a modified version of CEMSIM, a recursive bottom-up model built by the IPTS team (see [Szabo *et al.*, 2003; Szabo *et al.*, 2006], for a more thorough description). The demand side of the model is based on a commodity intensity curve and a price-elastic demand, while the supply part features seven production technologies, fuel switch, material switch and retrofiting⁵. GEO and CEMSIM are merged, allowing us to build a business-as-usual scenario until 2030 and three climate policy scenarios.

12. In section 1, we briefly describe GEO and CEMSIM. Then, we give in section 2 the results of our model for the Business-as-Usual scenario (BaU). In the third and fourth sections, we give the results for two scenarios with mitigation policies:

- A CO₂ tax or Emission Trading Scheme (ETS) with auctioned allowances and no revenue recycling (thereafter: "the climate policy") is implemented in the Kyoto Protocol Annex B countries (except the USA and Australia), with two modelling variants (isoelastic and linear demand curves);
- The climate policy is implemented with a Border-tax adjustment (BTA), *i.e.*, a rebate on cement exports and a taxation of imported cement. We test two BTAs: In the first one, exported production is completely exempted from the climate policy and imports of cement from the rest of the world are taxed in accordance with the CO₂ intensity of the cement production in the exporting country. In the second BTA scenario, exports benefit from a rebate corresponding only to the least CO₂-intensive technology available at a large scale, and imports are taxed to the same level. Such a scenario is proposed by Ismer and Neuhoff [Ismer and Neuhoff, 2004] who argue that it is compatible with the WTO rules, contrary to the first one we test.

13. Then, we conclude. Annexes I, II and III present respectively the GEO model, the GEOcp model and the CEMSIM-GEO model in more depth. Annex IV details the technical evolutions in cement production.

⁵. Retrofitting means a switch from one technology to another in an existing plant, which is done in the model if it is technologically feasible and economically rational. For further details, see Annex III.

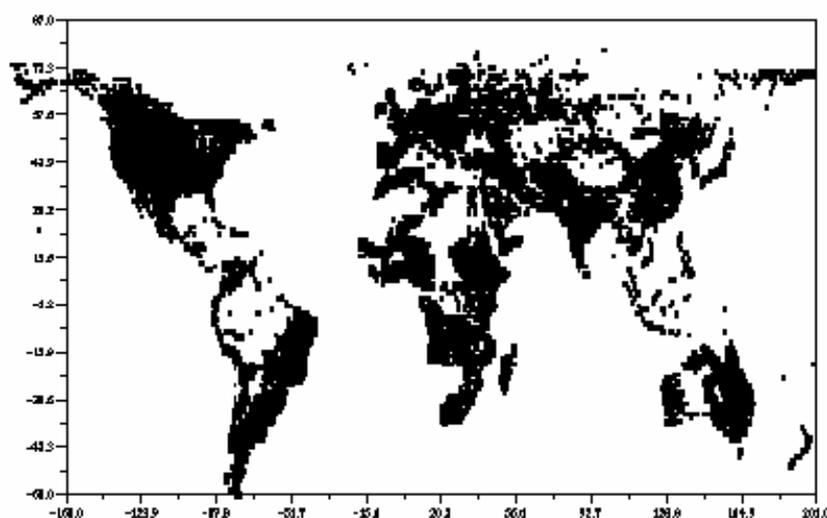
THE CEMSIM-GEO MODEL

14. Thereafter, we briefly present the GEO and the CEMSIM models. For further details, see Annexes I and III.

GEO

15. In the spatial model GEO, the world is modelled as a combination of cement consumption areas – thereafter only referred to as "areas" – on the one hand and producing countries on the other hand⁶. An area is characterized by its geographical position on the globe and its consumption. Areas used by GEO are the 1°x 1° squares defined in the EDGAR database [RIVM, 2001], but we subdivided squares with a high population and dropped squares where the population is negligible (figure 1). In each of the 15 500 areas, we assume that only one producing country takes the market.

Figure 1: Areas of GEO



16. A producing country is characterized by its variable production cost, its production capacity and the intensity of the competition among its domestic producers. We assume that a Cournot⁷ oligopoly competition takes place among producers of the same country, since it is well known that the cement market is far from pure competition (see for example [Johnson and Parkman, 1983; EC, 1994]). A country is also characterized by the geographical position of its harbours for trade. The 1 600 sea harbours able to

⁶ Areas, grouped together, form consuming countries. In GEO we have the same 47 consuming and producing countries. These countries are the ones of the POLES nomenclature.

⁷ With Cournot (quantity) competition, the firms take into account the negative effect of an increase in their sales on price and then on their profit. Therefore, compared to pure competition, they limit their production, so the resulting price is over their marginal cost. Their profit is then higher than under pure competition, although less than under monopoly. The more firms on the market, the more the equilibrium tends toward perfect competition.

trade cement according to the Lloyd's list [Lloyd, 2004] are taken into account, and 7 500 land harbours are defined every 25 km on land borders.

17. GEO then calculates the minimum transportation cost from every producing country to every consuming area, using road national transport costs and international sea transport costs. A fixed and a variable transportation cost are distinguished for each transportation mode.

18. We assume that a producing country is ready to sell its production in an area at any price bigger than the sum of its variable cost and the transportation cost to this area, subject to a capacity constraint. When the latter is binding, a producing country sells its production in the most profitable areas. Of course, the set of "most profitable areas" depends on other producing countries' behaviour; hence the need for an adequate algorithm to determine simultaneously what supplier takes each area. The cement price a firm applies in an area is limited by a double competition pressure:

- International pressure from the other producing countries (Bertrand competition⁸), and
- National pressure from firms of the same producing country (Cournot competition). The number of firms in the Cournot model is calibrated to match the profit margin⁹ in the calibration year (1997), and assumed identical thereafter.

19. In every area, the cement supplier thus applies a profit margin which is the minimum between the profit margin defined by the international pressure and the profit margin defined by the national oligopolistic competition. Using the variable cost and capacity constraint of every country as well as the minimum transportation cost between every producing country and every consuming area, GEO gives for every area the cement price and where it comes from. At the aggregated level, it gives for every producing country the production, the capacity utilisation rate and the profit (on variable production cost and transportation cost), and for every consuming country the average cement price (which is the weighted sum of the prices in the areas of this country).

20. Every country has a capacity constraint, which is not fixed but may be relaxed every year by investing in new capacities. GEOcp, a modified version of GEO, is used also to estimate the construction of new capacities, which occurs when the fixed cost of the new capacity does not prevent it to win at least one area against the existing available capacities of the other producers (if any). For further details on the GEOcp model, see Annex II.

21. Some caveats are in order. First, we model no inertia in trade, whereas in the real world, for a cement manufacturer, exporting in a new market takes some time, notably to develop a distribution network. As a consequence, real-world changes are likely to be smoother than modelled. Second, the assumption of Bertrand competition among producers of different countries seems too harsh since there is some oligopolistic behaviour among them. However, it is the best compromise we found to date between modelling constraints and realism.

CEMSIM

22. For a given cement price, consumption is driven by the "intensity of use hypothesis": an inverted U-shape curve explains the time evolution of cement consumption per unit of GDP. As in the original

⁸ With Bertrand (price) competition, the firms apply a price which equals their marginal cost. The resulting equilibrium is similar to the perfect competition one.

⁹ We define profit margin as the ratio (cement price - variable production cost - transportation cost) / (variable production cost + transportation cost).

CEMSIM IPTS model, the demand curve for cement is assumed isoelastic, with a price-elasticity of 0.2, a value close to that estimated by La Cour and Mollgaard ([La Cour and Mollgaard, 2002], cited and used by [IEA, 2004]).

23. CEMSIM pays particular attention to technology dynamics. Seven technologies are included, characterized by energy, material and labour consumptions, an investment cost and a set of retrofitting options. We modified the original CEMSIM IPTS model to introduce more flexibility in the clinker content of cement and in the choice of fuels.

24. We stress that the quantification of some technical flexibility (clinker ratio, retrofitting, fuel choice) is very difficult, so our quantitative results should be taken with some care.

25. The main exogenous variables of CEMSIM are GDP, population, electricity and primary fuel prices, all taken from POLES. Prices of other fuels (waste and wood fuels, petroleum coke) are calibrated.

26. We use 1998 and 1997 data on consumption, production capacity, energy demand [CEMBUREAU, 1999b; CEMBUREAU, 2002] and cement bilateral trade (OECD series C) to calibrate the CEMSIM-GEO model, which is then recursively run with a yearly step.

The business-as-usual scenario (BaU)

27. The BaU is a necessary preliminary step to assess the impacts of the climate policy, and already provides interesting insights. To present the results, we aggregate the 47 producing countries of CEMSIM-GEO to form 12 regions:

- **Europe** : EU25, Bulgaria, Romania and the rest of western Europe,
- **R&U**: Russia and the Ukraine,
- Japan,
- Canada,
- The USA,
- **RJAN**: Rest of Japan, Australia and New Zealand (Mostly Australia and New-Zealand),
- **TRR**: Turkey, Rest of the CIS and Rest of Central and Eastern Europe,
- **LAM**: Latin America,
- India,
- China,
- **RoA**: Rest of Asia,
- **A&ME**: Africa and Middle-East.

28. The first four regions are the ones that have ratified the Kyoto Protocol and that will implement the climate policy with and without Border-Tax Adjustments in the next sections. We label them the Annex B countries, or simply the Annex B, although the USA and Australia are not part of them¹⁰.

¹⁰ Unfortunately, since New Zealand is merged with Australia in our set of 47 producing countries, we have to assume that it does not implement the climate policy although it has ratified the Kyoto Protocol.

Production Costs

29. We distinguish two production costs: the variable production cost (including energy cost, raw material cost and variable operation and maintenance cost) and the fixed production cost (investment cost and fixed operation and maintenance cost). We consider, through GEO, that the determining factor of the international competition, when production capacities are fixed, is the variable production cost. That is why we focus on it and on its evolution through time in this section.

30. The national variable production costs are driven by energy costs¹¹: electric energy and fuel energy. It is worth noting that at the world level energy cost account for more than half of the variable production cost of a tonne of cement, fuel energy cost for 65% of the energy cost and electric energy cost for 35% of the energy cost.

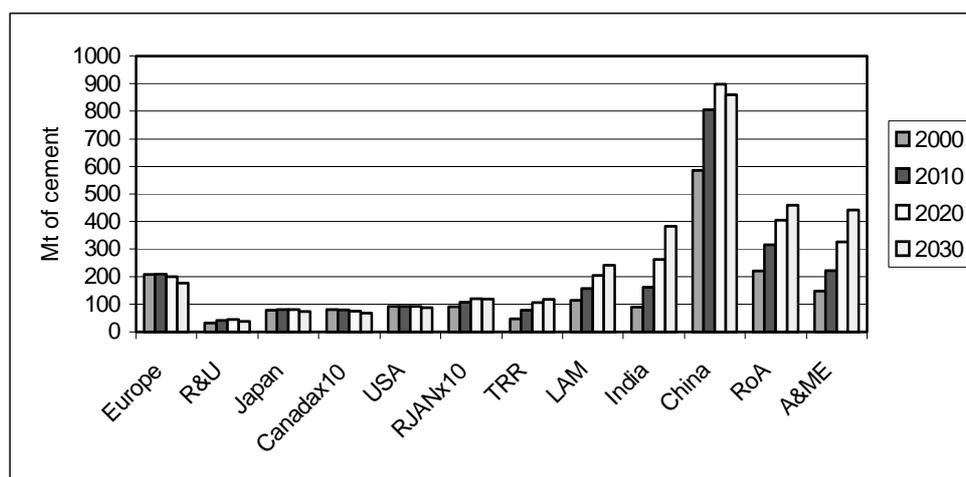
31. According to CEMSIM-GEO, the fuel and electric energy consumptions per tonne of cement drop significantly throughout the world between 2000 and 2030: by around 25% in average. These energy efficiency improvements are not due to the decrease in the national clinker rates¹²: at the world level, the average clinker rate remains almost around 85%. They are mostly due to the fact that every year the new machines available are more efficient, and also to the switch from low to high efficiency technologies through the retrofitting of existing capacities or in the building of plants. These worldwide energy efficiency improvements offset the almost worldwide increase in energy costs: the world average variable production cost slightly decreases between 2000 and 2030.

32. For further details on the technological evolutions in the cement industry under BaU, see Annex IV.

Consumption

33. At the world level, cement consumption is estimated to increase from 1630 Mt in 2000 to 2900 Mt in 2030, corresponding to an annual 2% growth rate.

Figure 2: BaU / Consumption



¹¹ Variable operation and maintenance costs and the raw material cost are assumed to be constant through time.

¹² Clinker is the energy-intensive and CO₂-intensive intermediary product in the cement manufacturing process.

34. At the regional level, the evolution of cement consumption is highly dependent on the inverted U shape hypothesis for the consumption path. The model predicts a high growth in developing regions. China reaches its maximum around 2020, consuming 900 Mt, and from then on its consumption level decreases slightly. Similarly, R&U peaks around 2020 with 45 Mt consumed. In 2030, the last simulation year, Indian consumption is still growing (90 Mt in 2000, 390 in 2030). The same stands for TRR, A&ME, LAM and RoA.

35. No developed region (Europe, Japan, Canada, the USA and RJAN) sees its consumption growing after 2020. Cement consumption decreases after 2020 in RJAN, after 2010 in the USA, in Japan and in Europe and from the start in Canada. Whereas these regions represented 24% of the world consumption in 2000, they are projected to only represent 13% in 2030.

International trade

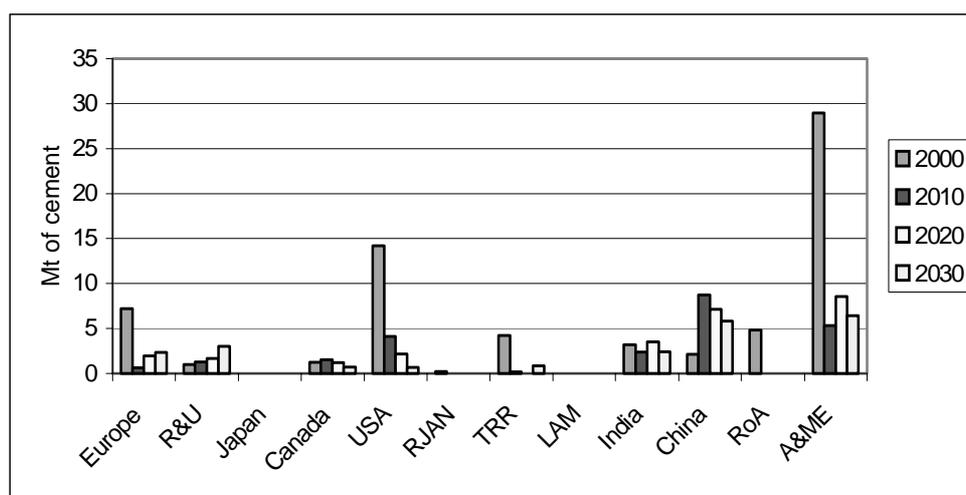
36. In general, international trade is due to the difference in variable production costs. In a few cases, it is due to a lack of production capacities in the importing country – *e.g.*, in the Netherlands around 2000. In some cases, Rest of South East Asia (RSEA) for example, exports are limited by the production capacity: if it had more capacity, RSEA would export more.

37. Some limited capacities are built in order to export, but most exports come from what we label "domestic overcapacities", *i.e.* capacities built for the domestic market but that are not fully used for it. According to industry experts [LAFARGE, 2004], until now, almost all the international trade in cement has been triggered by this mechanism.

38. The intensity of the international trade drops between 2002 and 2004 from 7 to 4% of world production, mostly because of the significant increase in sea transportation costs: +50% between these two time periods. Then, independently of transportation costs which remain constant, it keeps on decreasing to reach 2% in 2008 and then slightly decreases until 2030.

39. For the regional description of cement trade we focus on the Annex B countries that will implement in the following sections various climate policies.

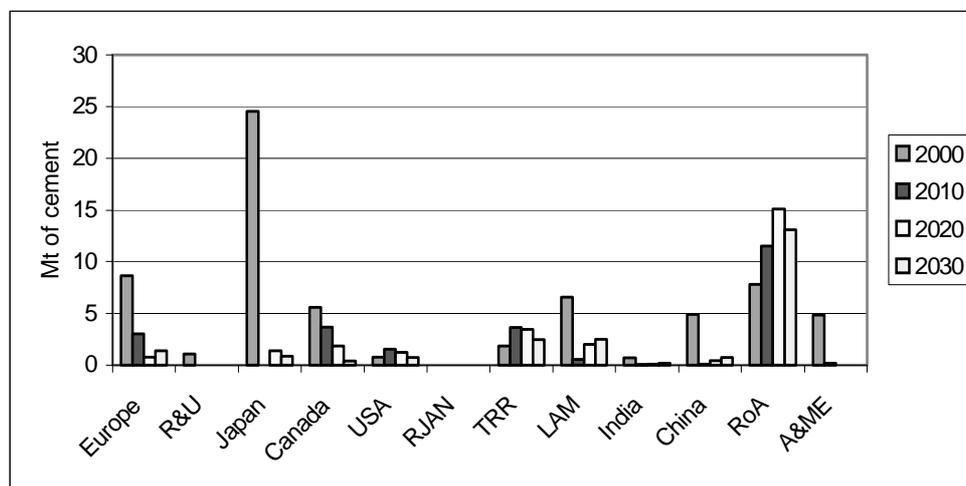
Figure 3: BaU / Imports



40. We observe that Europe imports cement around 2000, mostly from LAM, RoA, TRR, A&ME and R&U. After the increase in sea transportation costs between 2002 and 2004, European imports drop. The most important exporters to Europe are TRR and A&ME around 2010, TRR and mostly LAM around

2020 and 2030. R&U imports some cement during all the simulation from Europe, TRR, RoA and China. Japan does not import cement. Canada imports cement from LAM, Europe and mostly from the USA in 2000. After the increase in sea transportation costs, it only imports cement from the USA.

Figure 4: BaU / Exports



41. Around 2000, Europe exports cement to Canada, R&U, TRR and the USA but mostly to A&ME. Between 2010 and 2030, European exports drop and focus mainly on the nearest countries. R&U exports some cement to Europe and TRR in 2000. Japan exports around 2000 cement to RJAN, RoA, and mostly to A&ME. After the increase in sea transportation costs, Japanese exports drop. However, it keeps on exporting some cement to A&ME. Canada exports cement to the USA during all the simulation.

42. It is worth noting the fact that, according to our model, and as in the reality, a country A may import cement from a country B and, in the same time, export to a country C. This fact has various grounds:

- A has a privileged position to export to C compared to B, whereas B has a lower production cost than A, or
- B prefers to use its capacities to export to A, where the market is more profitable, than to C.

43. It highlights the need for a relevant treatment of the barriers to trade, especially transportation costs, and of the capacity shortages, what we do through GEO.

Production

44. For most of the countries, cement trade is marginal. Two exceptions are Japan in 2000, for which exports represent up to 20% of its production, and Canada in 2000, for which exports represent up to 30% of its production. Finally, in almost all countries, production nearly equals consumption.

CO₂ emissions

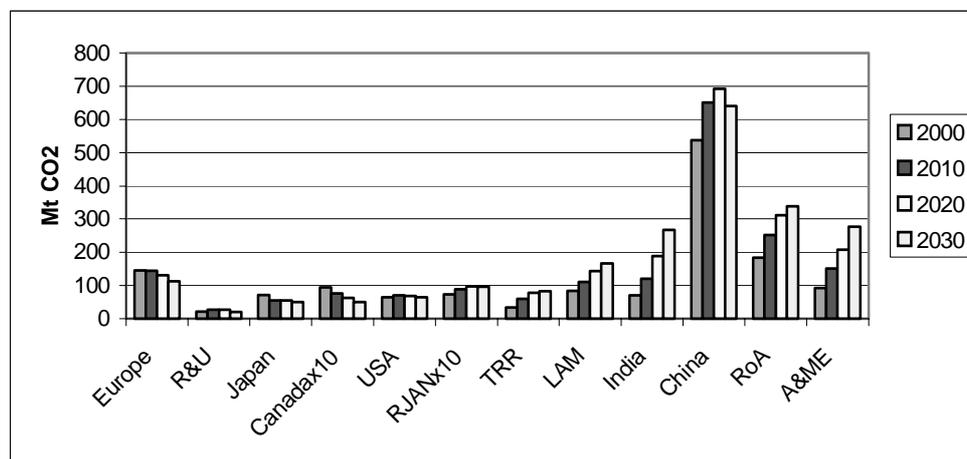
45. In the cement industry, around 40% of CO₂ emissions are due to fuel combustion and around 60% to the process itself¹³. The former may be reduced by switching towards less carbon intensive fuels,

¹³ We do not take into account, in the computation of the CO₂ emissions of the cement industry, the emissions induced by the electric consumption. However, when CO₂ mitigation policies will be

improving energy efficiency and reducing the share of clinker in cement but the latter may only be cut by reducing the share of clinker in cement.

46. CO₂ emissions are projected to grow by 55% from 1320 Mt CO₂ in 2000 to 2035 in 2030, *i.e.* a 1.5% average annual growth rate.

Figure 5: BaU / CO₂ emissions



47. China accounts for 40% of CO₂ emissions from cement manufacturing in the world in 2000. In 2030, it accounts “only” for 31% but remains the largest CO₂ emitter. Developed regions represent together 22% of world emissions in 2000 and only 12% in 2030.

48. At the world level, we notice that, between 2000 and 2030, the emission growth is lower than the consumption growth. The world emission intensity decreases, from 810 kg of CO₂ per tonne of cement in 2000 to 700 in 2030 (-14%). This decrease is not due to a reduction of the clinker content, but to a decrease in fuel consumption per ton of cement and to the use of less carbon intensive fuels, like the waste and wood fuels which cause, according to our assumptions, no net CO₂ emissions.

49. For further details on the drop of the CO₂ emissions per tonne of cement in BaU, see Annex IV.

Profit Margins and Prices

50. In this report the “profit margin” is the profit margin on variable cost, *i.e.* is defined as (price – variable cost – transportation cost) / (variable cost + transportation cost).

51. The profit margin that a producing country applies in an area where it is the most cost competitive depends on:

- The national pressure from firms of the same producing country,
- The international pressure of the other producing countries in this zone.

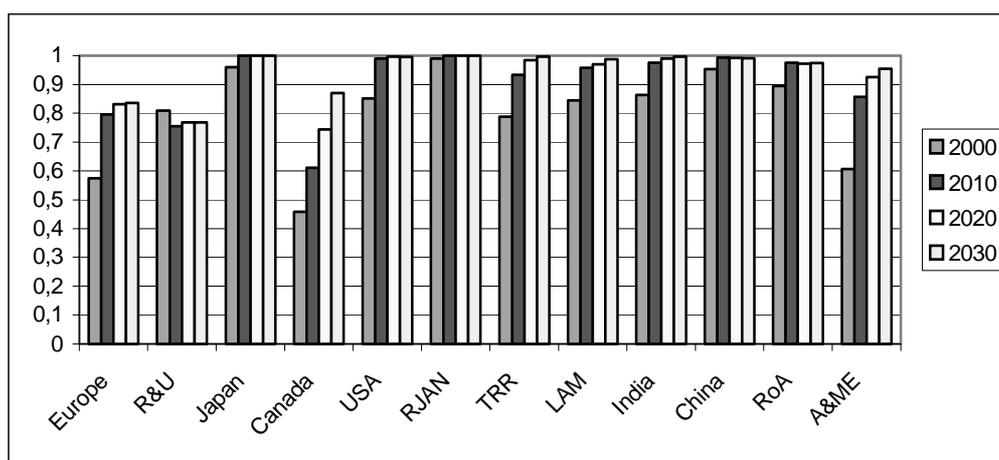
52. The international pressure of a country does not only depend on its cost competitiveness in this area: a cost competitive country will not put price pressure in this area if it does not have enough “price

implemented in the next sections, these emissions will be taken into account through the rise in the electric prices they imply.

pressure capacities”, the price pressure capacities being the capacities that it does not use to satisfy the demand of its own market area (domestic market area and export market area)¹⁴.

53. We name "maximal profit margin of a country" the profit margin applied by its producers when there is no international pressure. The maximal profit margin is determined by the oligopolistic competition among the producers of this country¹⁵. In the following figure, we represent the evolution of the ratio: average profit margin applied by a country on its own territory (domestic profit margin) over its maximal profit margin.

Figure 6: BaU / domestic profit margin / maximal profit margin



54. We notice that in all regions except R&U, the domestic profit margin increases between 2000 and 2010. This is due to the significant rise in sea transportation costs between 2002 and 2004 which leads the international pressure to soften. This rise, which partially protects the domestic producers, is offset in the R&U case by the deterioration of its cost competitiveness - due to the significant rise in energy prices in this region.

55. After 2010, the domestic profit margin in every region moves slightly, depending on the evolution of the cost competitiveness of every country vis-à-vis its competitors. It is worth noting the Canadian case which highlights the importance of the price pressure capacities in the international pressure. According to our model, the average profit margin the Canadian manufacturers apply in their country keeps on increasing after 2010, whereas its cost competitiveness vis-à-vis the USA, its direct competitor, does not improve. It is due to the fact that, after this time period, the amount of price pressure capacities in the USA decreases. Indeed, domestic overcapacity in the USA drops after 2010, following the slow down of the consumption growth (see Annex II).

56. The rise in domestic profit margins applied by cement manufacturers offsets the drop in their variable production costs: at the world level, the cement price slightly increases between 2000 and 2030 from 55 to 58€ per tonne of cement.

¹⁴ For further details see Annex I.

¹⁵ Until now, we assume that the demand is isoelastic. Under this assumption, the maximal profit margin is constant through time. Indeed, the maximal profit margin of a country is mathematically defined by

$$\mu = \frac{1}{N \cdot \varepsilon - 1},$$

where N is the number of firms in the country and ε the price elasticity of the cement demand. With an isoelastic demand, ε is constant, and so is the maximal profit margin.

THE “CLIMATE POLICY WITHOUT BORDER-TAX ADJUSTMENT” SCENARIO ("NO BTA")

Definition of No BTA

57. In this scenario, we assume that Europe, R&U (Russia and the Ukraine), Japan and Canada¹⁶ implement a CO₂ tax or a CO₂ Emission Trading Scheme¹⁷ with auctioned allowances, without revenue recycling (thereafter: "the climate policy"). For 2008-2012, we rely on the estimation of the POLES model, assuming that Russia and the Ukraine use their market power to raise the international CO₂ price, which would then reach 15 euros per tonne [Szabo *et al.*, 2003]. Finally we assume that this price is sustained until the end of the simulation period and that neither the USA nor developing countries take on emission targets until 2030. This is not the most likely outcome of future climate negotiation, but has the advantage of simplicity. At last, we assume no Clean Development Mechanism.

58. The CO₂ value triggers different mechanisms in CEMSIM-GEO: reduction of cement demand due to the increase in production costs and hence in prices; substitution between clinker (the CO₂ intensive product) and added materials in cement composition; substitution between high and low carbon fuels (from coal, oil and petroleum coke to gas, waste and wood fuels); retrofitting of CO₂ intensive technologies to low CO₂ technologies; changes in technological choices for new plants. Moreover, non-global climate policies modify the competition terms, and consequently impact the equilibrium between producing countries on the world cement market.

59. We label this scenario “No Border-Tax Adjustment”, or simply “No BTA”, in opposition with the scenarios of the following section where we will test the implementation of Border-Tax Adjustments (BTA). Thereafter, we present the results of No BTA in comparison with BaU.

Production Cost

60. With the implementation of the climate policy, Annex B producers face a CO₂ price. This price leads them to decrease their emissions per tonne of cement. We can distinguish three way of reducing the specific emissions: reduction of the clinker rate, improvement of the energy efficiency and use of low carbon fuels. We observe that they succeed in reducing the content of clinker in cement (-11% in 2010, 2020 and 2030 in average) and the emissions per TOE of fuel used (-3% in 2010, 11% in 2020 and 15% in 2030 in average). On the contrary, their energy efficiency per tonne of clinker slightly decreases. Finally, in No BTA, variable production costs in Annex B countries increase in average by 10 € per tonne of cement (+30%) from 2008 on. For further details on these points, see Annex IV.

¹⁶ Unfortunately, since New Zealand is merged with Australia in our set of 47 producing countries, we have to assume that it does not implement the climate policy although it has ratified the Kyoto Protocol.

¹⁷ We stress that in the EU ETS, allowances are not auctioned but given for free, and the quantity distributed is influenced by their decisions. In particular, a firm closing an installation will generally stop received allowances and conversely, free allowances are distributed for new installations [Schleich and Betz, 2005]. As a consequence, the competitiveness impact of the EU ETS and its impact on emissions will be much lower than that of the policy we simulate, for a given CO₂ price.

61. It is worth noting that, from the production cost point of view, non Annex B countries generally benefit from the implementation of climate policies which leads to the decrease in fuel prices.

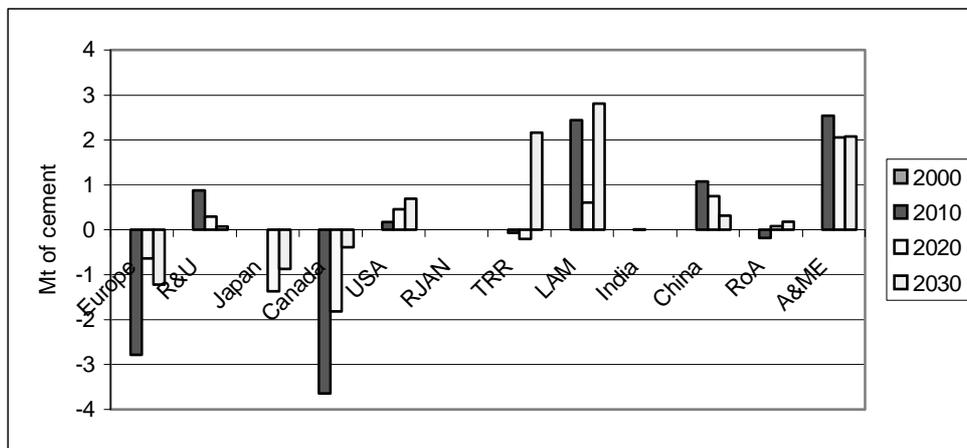
Consumption

62. The significant increase in variable production costs in Annex B countries and the slight decrease in their profit margins, as we will see below, lead cement prices in these countries to rise by 21% in average in 2010 (25% in 2020, 24% in 2030). Consequently, consumption drops in average by 3% (4% in 2020 and 2030).

International trade

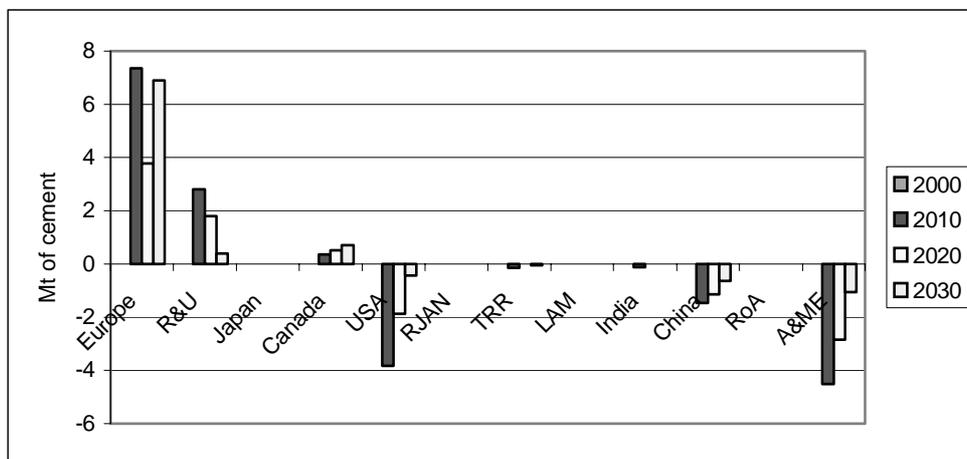
63. The significant increase in the variable production cost of Annex B countries, hence on their cost competitiveness, largely modifies the international competition represented through GEO.

Figure 7: No BTA / change in Exports compared to BaU



64. From the implementation of the climate policy, Europe stops to export to A&ME, TRR and R&U, Canada stops exporting to the USA and Japan stops exporting to A&ME. Inversely, R&U increases its exports to Europe. Indeed, R&U proves to be less impacted by the climate policy than European countries (see Annex IV).

Figure 8: No BTA / change in Imports compared to BaU



65. Europe increases its imports from TRR and mostly from LAM and A&ME, and starts to import some cement from R&U. European imports represent around 4% of its total consumption in 2010 in No BTA vs. less than 1% in BaU (3 vs. 1% in 2020 and 5 vs. 1% in 2030). Some limited export capacities are built in TRR from 2025 in order to export to Europe. R&U increases its imports from RoA and China and starts to import some cement from A&ME. In 2010, R&U imports 10% of its consumption whereas it imports only 3% in the BaU (8 vs. 4% in 2020, 9 vs. 8% in 2030). As in the BaU, Japan does not import cement in No BTA. On the contrary, Canada increases its imports from the USA and begins to import some cement from LAM. It imports around 26% of its consumption in 2010 vs. 19% in BaU (25 vs. 16% in 2020, 22 vs. 10% in 2030).

66. To sum up on this point, some countries prove to be very sensitive to the implementation of the climate policy. The sensitivity of Canada for example is mostly due to the fact that its population, and consequently its consumption, is localised near the USA-Canada border.

67. We notice that few export capacities are built in the countries that do not implement the climate policy. Transport and investment costs prevent cement manufacturers outside Annex B from building capacities designed to export, in spite of the consequent increase in the variable production costs in the Annex B countries. Exports keep on coming from domestic overcapacities that are not fully used for domestic consumption.

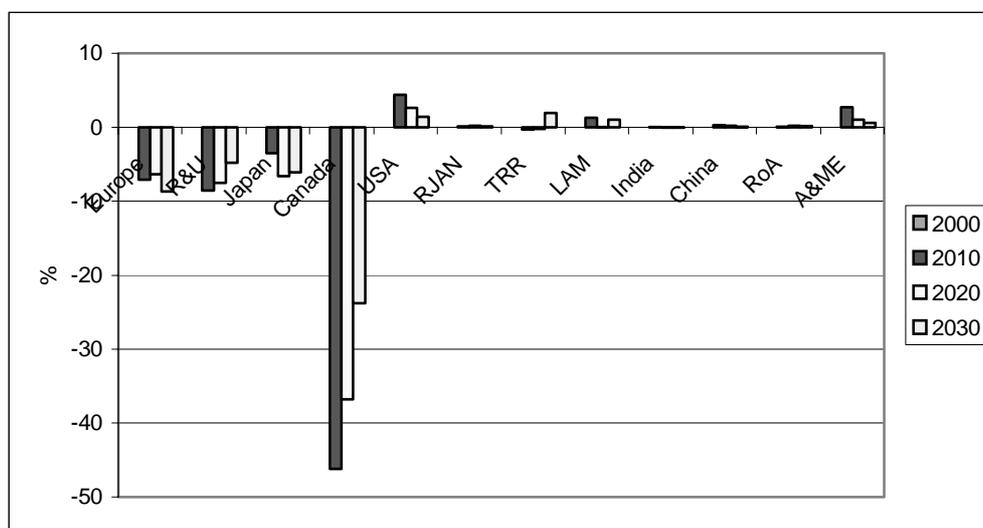
68. Furthermore, it is worth noting that in some countries that do not implement the climate policy, cement exports are not limited by transport costs but by production capacity. These countries are cost competitive enough to export more cement. Had they bigger domestic overcapacities, they would export more. This means that for an industry with high fixed costs like cement, the leakage rate is very dependent on the amount of domestic overcapacities, which is itself difficult to forecast.

Production

69. The growth in variable production costs highly impacts the production of Annex B countries for two reasons: the fall in consumption and the loss in cost competitiveness in the world cement market.

70. Finally, the production of the Annex B countries drops in average by 7.5% in 2010, 2020 and 2030. Inversely, the production increases in most of the other countries.

Figure 9: No BTA / Production compared to BaU

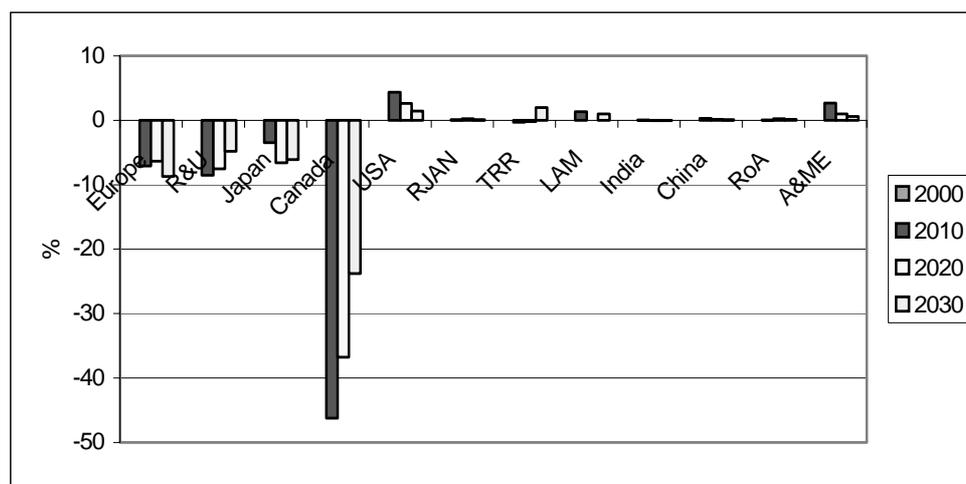


CO₂ emissions

71. Emissions per tonne of cement in Annex B countries decrease with the implementation of the climate policy: -12% in 2010, -14% in 2020 and -15% in 2030. The intensity of this drop differs across the Annex B countries. It is higher in R&U, which turns out to have more technical flexibility.

72. Adding the effect of the fall in production, emissions of Annex B countries are largely impacted: -18% in 2010, -20% in 2020 and -22% in 2030.

Figure 10: No BTA / CO₂ emissions compared to BaU



73. A part of these reductions are compensated by emissions increase in the non Annex B countries that export to Annex B: TRR, LAM, A&ME and the USA. These countries are less CO₂ efficient than Annex B countries and the gap increases with the implementation of the climate policy¹⁸.

74. The Annex B CO₂ leakage rate (emissions increase in countries outside the Annex B divided by the emissions decrease in Annex B countries) equals 25% in 2010, 13% in 2020 and 16% in 2030.

75. All in all, world emissions decrease by around 2% in 2010, 2020 and 2030. This amounts to a global emission reduction of 32 Mt CO₂ in 2010, 39 in 2020 and 34 Mt CO₂ in 2030.

Profit margins, Prices, Profits

76. With the implementation of the climate policy, the average profit margin applied by Annex B countries on their territory drops by 8% in 2010 (4% in 2020 and 2030). This drop only originates in the intensification of the international pressure (drop in the cost competitiveness of Annex B vis-à-vis non Annex B and rise in the amount of price pressure capacities inside Annex B with the drop in their consumption). The maximal profit margins of the Annex B countries do not fall. In other words, in the areas of their territory where they are not subjected to a significant international pressure, the Annex B

¹⁸

We notice that Chinese and Indian emissions decrease and that RJAN's emissions increase, marginally, although these countries are not impacted directly by the climate policy (they do not increase or decrease their imports or their exports compared to BaU). It is due to the fact that their consumption levels are indirectly impacted by the changes in the price pressure they face.

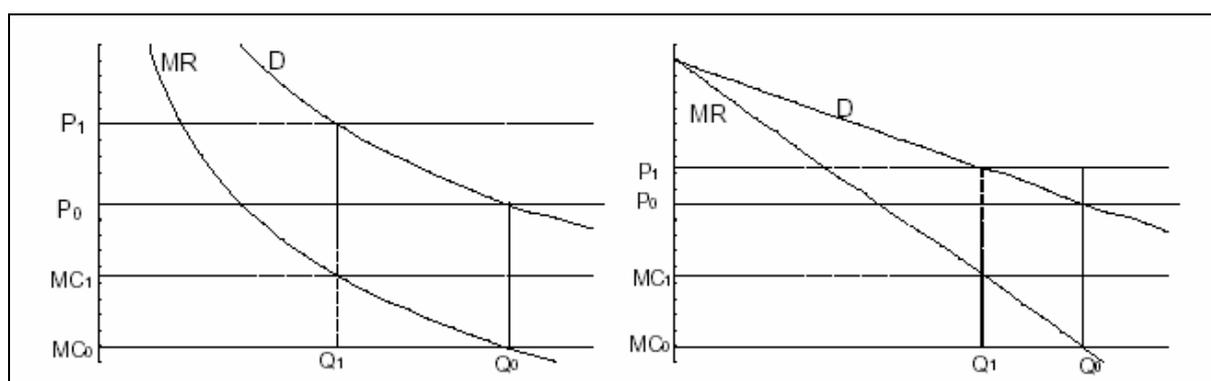
producers maintain the same maximal profit margin on their variable production cost than in BaU, in spite of its consequent increase by an emission cost. This is linked to the isoelastic demand assumption.

77. Indeed, until now and like in most models, national demand curves are assumed to be isoelastic. However there is no reason, apart from tractability and data availability, to assume that demand elasticities are constant on all the relevant portions of the demand function [Quirion, 2002]. This assumption is all the more controversial in a CO₂ constrained scenario which implies a large departure from the baseline conditions.

78. Furthermore, departing from this usual assumption may impact dramatically our results: behaviour of firms in a Cournot oligopoly competition is highly dependent on the demand curve shape. With a linear demand curve, when N profit-maximizing firms in Cournot competition see their variable production cost increase, a ratio $N/(N+1)$ of this increase is passed on to price: profit margin decreases [Ten Kate and Niels, 2004]. With an isoelastic demand curve, the profit margin remains constant. Impacts on prices and consequently on profits, consumption (the higher is the price, the lower is the demand), production and emissions are significant.

79. To understand better these differences, we present the case of a monopolist reacting to an increase in its variable production cost (from [Quirion, 2002]).

Figure 11: The shape of the demand curves matters for the competitiveness impacts



80. This figure represents the basic model of a monopoly: the firm chooses an output level by equalising the marginal receipts (MR) and marginal production costs (MC), and the price results from the demand curve (D) for this quantity. We suppose that following the introduction of emission trading, the marginal production cost curve, including the emission cost, rises from MC_0 to MC_1 . On the left panel, featuring an isoelastic demand curve, the output price rises by the same magnitude, from P_0 to P_1 , whereas on the right panel, with a linear demand curve, this monopolist is only able to pass half the surge in marginal production costs on to consumers.

81. To stress the importance of the assumption on the demand curve, we ran No BTA with a linear demand curve. Under this assumption, the average maximal profit margin inside Annex B decreases by 29% in 2010 (29% in 2020, 28% in 2030) and the average profit margin by 32% (29% in 2020, 28% in 2030) compared to BaU with a linear demand curve.

82. Therefore, the assumption made concerning the form of the demand curve highly impacts results on prices or profits (by profit, we mean the profit on variable cost):

83. Under the isoelastic assumption, cement prices in Annex B rise significantly: +21% in average in 2010 (25% in 2020, 24% in 2030). Consequently, consumption drops in average by 3% (4% in 2020 and 2030). But the rise in the profit realised per tonne of cement¹⁹ leads the profit of the Annex B to increase by 7% in 2010 (15% in 2020, 14% in 2030).

84. Under the linear assumption, cement prices in Annex B rise less: +8 % in average in 2010 (10% in 2020 and 2030). Therefore, consumption drops in average only by 1% (2% in 2020 and 2030). But the drop in the profit realised per tonne of cement²⁰ leads the profit of the Annex B to fall by 18% in 2010 (13% in 2020 and 2030).

85. It is emphasised that the profit we are talking about here is the profit on variable production cost. Thus, these results do not take into account the investment required to increase the carbon efficiency (retrofitting, modifications of the fuel combustion system...).

¹⁹ The profit per tonne of cement equals the profit margin multiplied by the variable production costs. The average profit margin inside the Annex B decreases by 8% in 2010 and 4% in 2020 and 2030, whereas the average variable production cost increases by 30% from 2010 to 2030. Therefore, the average profit per tonne of cement significantly increases inside the Annex B. However, it is not the case for all the countries of the Annex B.

²⁰ The average profit margin inside the Annex B decreases by 32% whereas the average variable production cost increases by 30%. Therefore, the average profit per tonne of cement inside the Annex B decreases.

THE “CLIMATE POLICY WITH BTA” SCENARIOS

Definition of the BTA scenarios

86. One way of preventing carbon leakage and limiting the effects on competitiveness of a non global climate policy is to impose Border-Tax Adjustments (BTA). BTA consist of two parts: some GHG-intensive products and materials exported to non Annex B countries are exempted from the climate policy; the importation of these products and materials from outside Annex B have to comply with it.

87. Using analytical models, several authors have demonstrated the rationale for BTA for dealing with international pollutions; cf. in particular [Markusen, 1975; Hoel, 1996; Mæstad, 1998]. In particular, Hoel showed that BTA are a better response to pollution leakage than the usually applied differentiation of the tax level between the exposed and the sheltered sector. More recently, Mathiesen and Mæstad [Mathiesen and Mæstad, 2002], with a partial equilibrium world model of the steel industry, and Majocchi and Missaglia [Majocchi and Missaglia, 2001], with a general equilibrium model, quantified the impact of BTA. It turned out that BTA prove to be efficient in order to bring a significant level of CO₂ abatement while preventing an adverse impact on the domestic industry.

88. Below, we assess this system in the “Complete BTA” scenario, in which the previous climate policy is implemented with the BTA described above.

89. However, the compatibility of BTA with the WTO/GATT is controversial and has generated a large literature in international law; see Hoerner (1998) for an early discussion and Ismer and Neuhoff (2004) for an up-to-date synthesis. The latter two authors conclude that to be WTO-compatible, the BTA should be set “at the level of additional costs incurred for procurement of CO₂ emission permits during production of processed materials using the best available technology”. Otherwise, claim Ismer and Neuhoff, some imported products would be subject to higher taxes than domestic producers, which would violate the General Agreement on Tariffs and Trade, art. III:2. Being no lawyers, we do not push this discussion further, but provide a quantitative application of the BTA proposed by Ismer and Neuhoff: in the "WTO BTA" scenario, the previous climate policy is implemented with the BTA they proposed. We take as best available technology the dry rotary kiln with pre-heater and pre-calciner fuelled by natural gas²¹.

90. In the rest of this section, we address two questions: do the two BTA scenarios effectively prevent the CO₂ leakage induced by the climate policy, and how these systems impact competition position of Annex B vis-à-vis non Annex B producers? In the following graphs, we thus present the results of the two BTA scenarios, for Annex B and non-Annex B countries in aggregate, for 2010 only, and in comparison with BaU. Demand is assumed to be isoelastic.

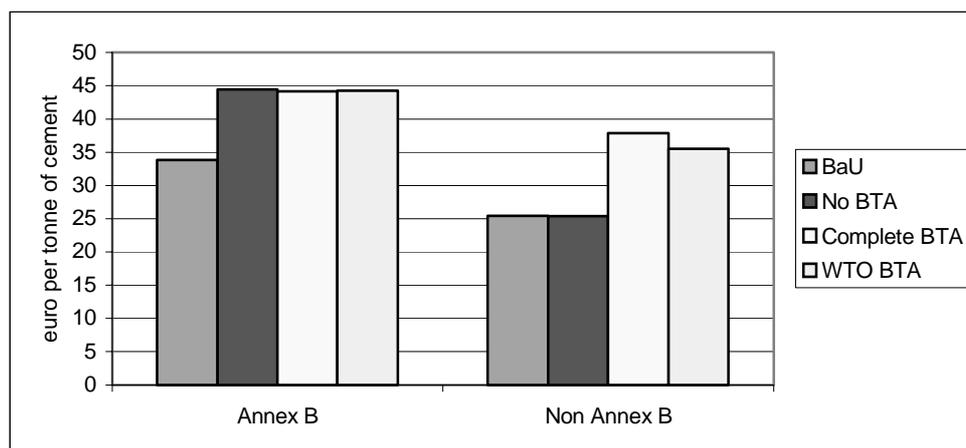
²¹ An even less CO₂ intensive solution is to burn waste and wood fuels instead of gas, but since we assume that this solution may not be generalised because of the limited availability of these fuels, we did not retain it as "the best available technology".

Production costs and cost-competitiveness

Annex B markets

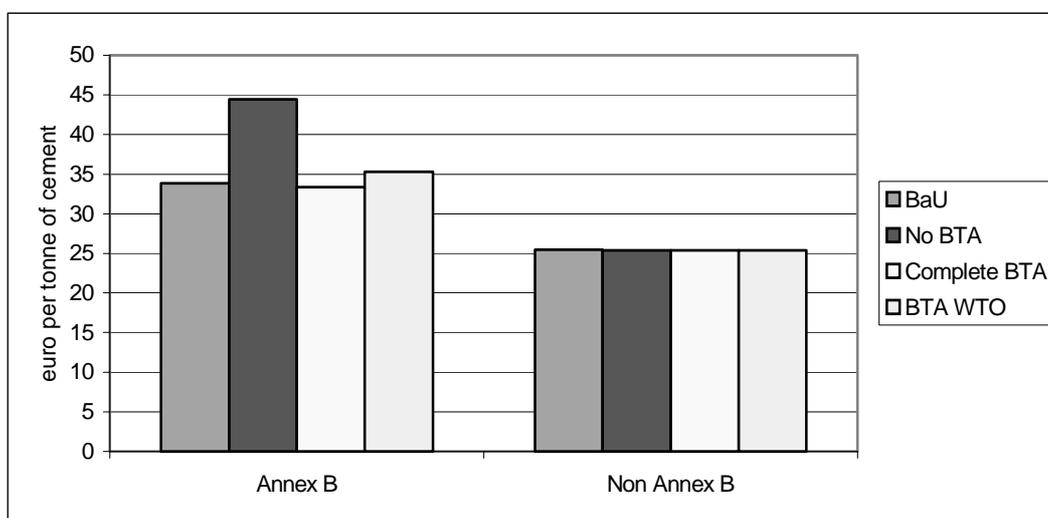
91. On the cement markets inside Annex B, every country's variable production cost increases by an emission cost, which varies from country to country in accordance to the CO₂ intensity of its production.

Figure 12: Variable production + emission cost in 2010 on Annex B markets



92. Under the Complete BTA, Annex B variable production cost in Annex B markets increases in average by 10.5€ per tonne of cement in 2010. It increases in average by 12.5€ for the non Annex B countries. Thus, competition terms on Annex B markets are modified in favour of Annex B countries, which are in general more carbon efficient than the others. Indeed, not only do they use more energy efficient technologies and less carbon intensive fuels already in BaU, but the climate policy also leads them to reduce their CO₂ emissions per tonne of cement (especially by decreasing their clinker rates), while non Annex B countries do not. Therefore the system implemented tends to improve the cost competitiveness of Annex B countries in their territory.

93. Under the WTO BTA, the emission cost for non Annex B countries in Annex B markets is limited by the one of the less carbon intensive technology. Their variable production cost increases in average by 10€ in 2010. Therefore, the WTO BTA system does not improve the cost competitiveness of Annex B countries on their territory vis-à-vis non Annex B countries.

*Non-Annex B markets***Figure 13: Variable production + emission cost in 2010 on non-Annex B markets**

94. In the markets outside Annex B, the Complete BTA still has impacts on variable production costs, even if there is no emission cost:

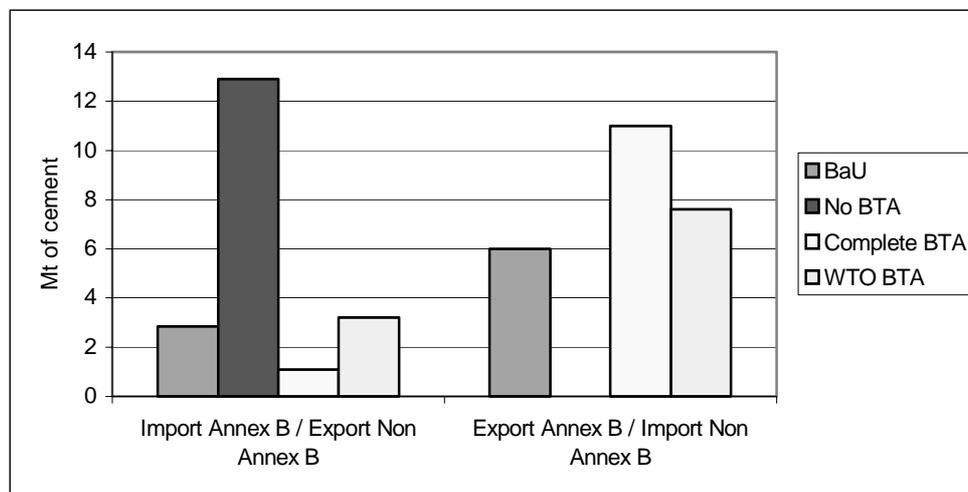
- On the one hand, countries implementing the climate policy increase their energy efficiency by investing in new technologies. The carbon price speeds up the natural evolution towards more energy efficiency.
- On the other hand, their average fuel costs increase (in general). This is due to the higher resort to low C fuels that are, most of the time, more expensive.

95. Finally, we observe that most of the Annex B countries increase their cost-competitiveness on the markets outside their territory in 2010 (-0.5€ in average). However these gains only last a few years after the implementation of the system.

96. Under the WTO BTA, the cost-competitiveness of Annex B countries on the non Annex B markets suffers a bit since the subsidies do not cover entirely their emission cost. Their variable production cost increases, in average by 1.5€ in 2010.

International trade

Figure 14: Imports and Exports in 2010



Annex B markets

97. In the Complete BTA scenario, as we have just seen, Annex B countries increase in general their cost competitiveness inside their territory. Therefore non Annex B countries lose some market shares. On this ground, the Complete BTA could be attacked as protectionist vis-à-vis non-Annex B countries. Annex B countries decrease their imports not only because of the increase in their competitiveness but also because the cement price increase makes their consumption drop.

98. Under the WTO BTA scenario, Annex B countries import more cement from non-Annex B countries than in the Complete BTA scenario, but also more than in BaU, since their cost-competitiveness is a little bit reduced. The WTO BTA is thus not protectionist vis-à-vis non-Annex B countries.

Non-Annex B markets

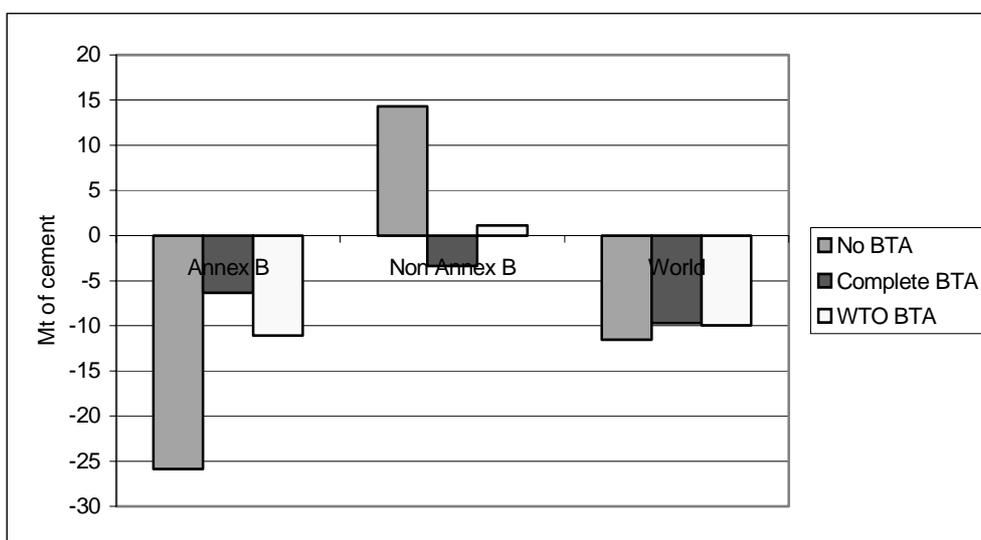
99. In the Complete BTA scenario, but also, to a smaller extent, in the WTO BTA scenario, Annex B countries increase their exports to non-Annex B. In the latter case, this is due to the increase in capacities available for exports, following the drop in consumption in these countries, which more than compensates the small decrease in cost competitiveness vis-à-vis non-Annex B countries. In the Complete BTA case, this is also due to the temporarily increase of Annex B vis-à-vis non Annex B on non Annex B markets.

100. To sum up on the impact of BTA on trade and competitiveness, the Complete BTA scenario could be attacked as distorting competition in favour of Annex B countries because, although it treats domestic and foreign producers in a similar way (they pay the same cost per ton of CO₂), it gives a competitive advantage to Annex B producers, who use cleaner production techniques. On the contrary, in the WTO BTA scenario, Annex B countries suffer from a slightly higher cost increase than their competitors, which causes a small increase in their imports. However, as is apparent from the figure above, their exports rise despite this relative variable cost increase, because some of their production capacities become available for exports. Should the WTO BTA policy be considered as distorting competition in favour of Annex B countries because the net exports of Annex B countries increase compared to BaU?

This seems highly dubious since this increase in net exports originates only in the drop in domestic consumption, and would occur also following a macroeconomic recession, for example²².

Production

Figure 15: Production in 2010 compared to BaU



101. In the two BTA scenarios, domestic prices increase in Annex B countries more than without BTA. Consequently, consumption in Annex B drops more significantly: in average by 4% in 2010, vs. 3% in No BTA.

102. From the total production point of view, this drop is partially offset by the decrease in net imports. In the two BTA scenarios, the Annex B production drop is more than halved: production in Annex B decreases by 2% in 2010 under the Complete BTA, by 3% in 2010 under the WTO BTA, instead of 7.5%, in No BTA.

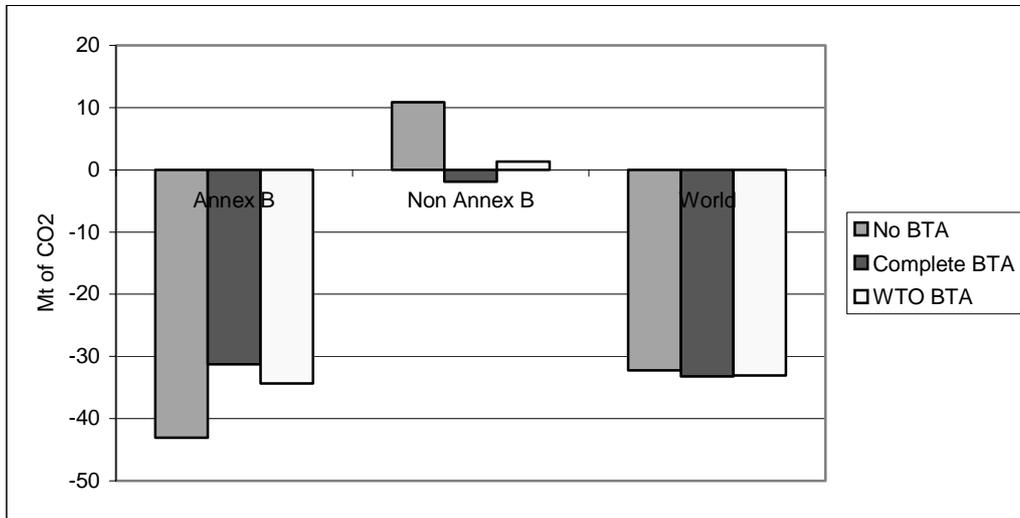
103. It is worth noting that under WTO BTA, total production actually rises a little in non-Annex B countries, which further reduces the rationale for attacking this scenario as distorting competition to the detriment of these countries. Indeed, average cement price in non-Annex B tends to decrease under the pressure of the Annex B, leading to the increase of the consumption. This rise offsets the increase in the net imports of non-Annex B in this scenario.

²²

Such a rise in cement exports happened in Asia after the 1997 crisis.

CO₂ emissions

Figure 16: Emission in 2010 compared to BaU

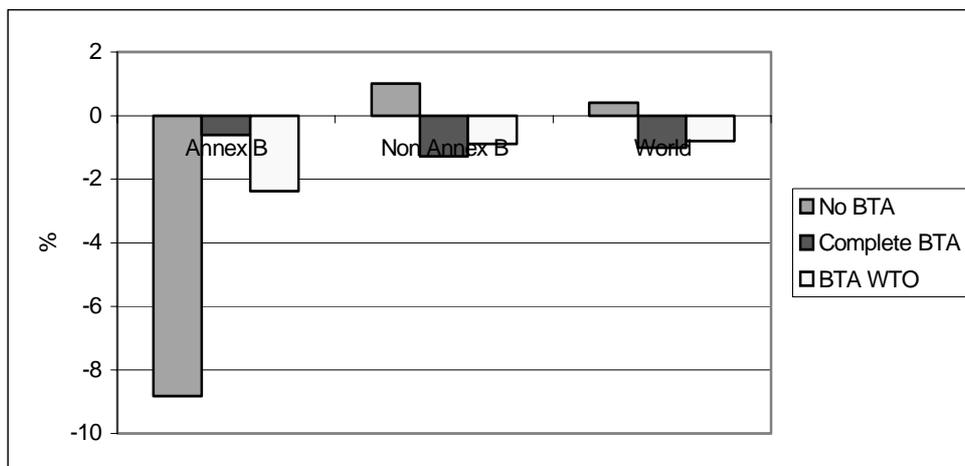


104. Under the Complete BTA, Annex B emissions decrease by 13.5%, *i.e.*, 31 Mt CO₂, in 2010, thanks to both a production drop and an improvement in the CO₂ efficiency of production. We notice that emissions from the rest of the world also decrease, although very slightly, due to a decrease in their production (around -0.1%). The spillover rate (abatment in non Annex B over abatment in Annex B) is 6%. Finally, world emissions decrease by 2%, a little more than under No BTA.

105. Under the WTO BTA, emissions from Annex B countries decrease more than in the Complete BTA scenario: -15%. This is due to the higher drop in their production level. Emissions from non Annex B increase a little compared to BaU, so that the slight spillover observed in the Complete BTA is replaced by a slight leakage: around 4% in 2010. The reduction in world emissions is a little lower than under the Complete BTA.

Profit Margins, Prices and Profits

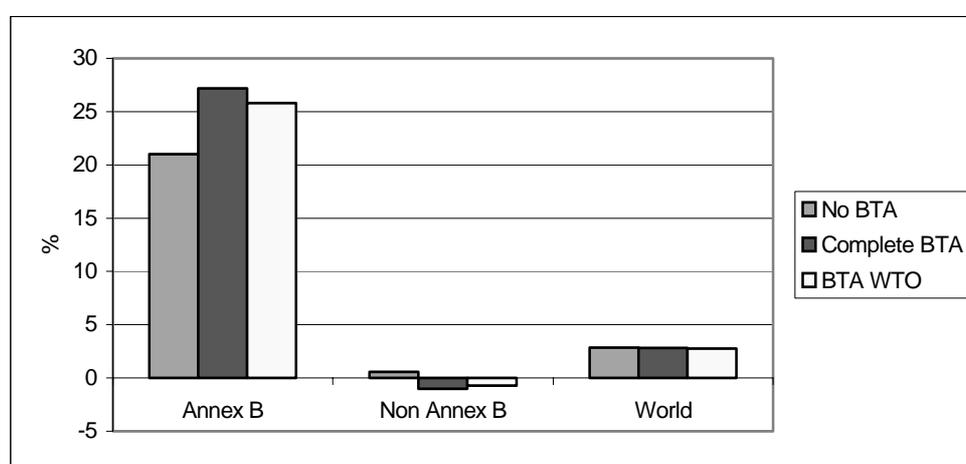
Figure 17: Domestic profit margins in 2010 compared to BaU



106. In the two BTA scenarios, Annex B producers are less stressed to decrease their profit margin on their territory than in No BTA, in accordance with the fact that they are totally or partially protected by these systems. It seems surprising that the domestic profit margins applied by the Annex B countries decrease, in average, under Complete BTA, because their cost competitiveness increases vis-à-vis non Annex B. This drop is in fact due to the rise in the amount of price pressure capacities, not only in non Annex B countries with the drop in their production, but also in Annex B countries with the drop in their consumption. This rise leads to the intensification of the international pressure.

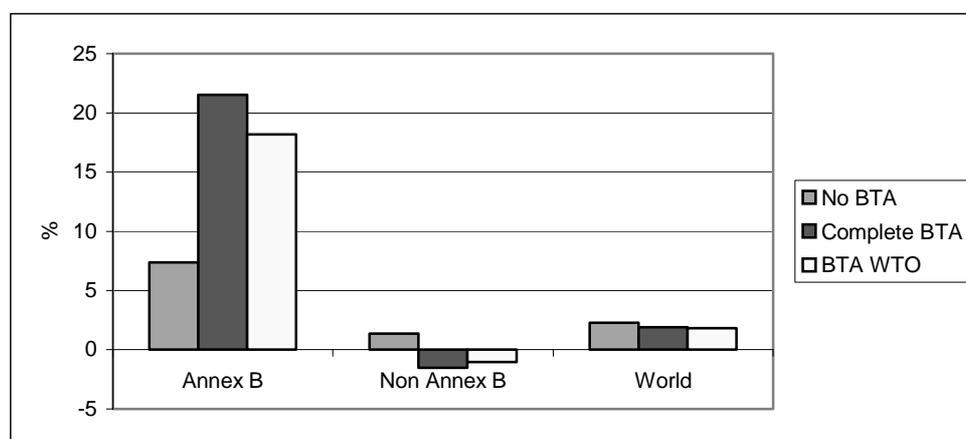
107. We notice that the non Annex B producers suffer from the intensification of the international pressure implied by these systems, through the increase in the amount of Annex B price pressure capacities in the WTO BTA case, and also through the increase in the price competitiveness of Annex B in the Complete BTA case.

Figure 18: Domestic prices in 2010 compared to BaU



108. In all CO₂ mitigation policy scenarios, the decrease in the profit margins in Annex B is offset by the consequent increase in their variable production costs, so that domestic prices increase significantly. This rise is more important in the two BTA scenarios than in No BTA, profit margins falling less. Concerning the non Annex B countries, the evolution of their domestic prices according to the policy implemented follows the one of the profit margins, their variable production costs being not impacted (or very marginally) by the carbon policies.

Figure 19: Profits in 2010 compared to BaU



109. Finally, in the two BTAs, the Annex B profit increases, as in No BTA. But the rise is more important, the production and the domestic profit margin falling less.

110. Let us remind that results on profit margins, prices and profits highly depend on the assumption on the demand curve, as it is highlighted in the previous section, and that the profit we are talking about is the profit on variable production cost.

Conclusion

111. In the cement sector, transportation costs and capacity constraints are central to explain international trade patterns. Therefore, it is worth dealing with these factors more explicitly than in the conventional Armington-based models. In this aim, we developed the international trade model GEO and merged it to the IPTS cement model CEMSIM.

112. The business-as-usual (BaU) scenario generated by the CEMSIM-GEO model forecasts an important increase in cement production (2%/yr in average until 2030), entailing an alarming rise in CO₂ emissions (1.5%/yr). The CO₂ efficiency thus rises by 0.5%/yr, thanks to a more intensive use of waste and wood fuels and to the increasing share of modern machines and more energy-efficient technologies.

113. Then we implement a CO₂ tax, equivalent to a CO₂ Emission Trading Scheme with auctioned allowances, without revenue recycling, in Annex B except the USA & Australia, at 15 euros per tonne. This climate policy entails a significant decrease in CO₂ emissions in these countries (around 20%), through a quicker penetration of energy-efficient technologies, a decrease in the rate of clinker (the CO₂ intensive input) in cement, a quicker switch to low carbon fuels (gas, waste and wood fuels) and a decrease in cement consumption. The impact on cement production in these countries is significant (-7.5% in 2010) because of both a cut in their domestic consumption level and a loss in competitiveness. For the latter reason, production and thus emissions in the rest of the world increase. The corresponding leakage rate is around 25% in 2010 (around 15% after), a result in the upper range of leakage estimates presented in the IPCC third assessment report (Hourcade and Shukla, 2001).

114. Our last two simulations focus on an efficient way of addressing this leakage: a border-tax adjustment (BTA), by which Annex B countries tax imports of cement from the rest of the world and exempt (at least partially) their exports to the rest of the world from the climate policy. We test two BTA scenarios. Under the more ambitious BTA, the loss in production of Annex B countries is limited to 2% instead of 7.5%, and the leakage is replaced by a spillover since emissions in the rest of the world decrease. The decrease in world emissions is a bit higher than without BTA. However, compared to business-as-usual, non-Annex B price-competitiveness decreases a little and they lose some market shares, so these countries could claim that this system distorts competition in favour of Annex B countries. A less ambitious BTA is thus tested, which cannot be criticised on this ground and prevents almost all leakage. The only drawback is that this BTA leads, as the previous one, to a higher increase in cement price and thus hurts consumers in Annex B countries.

115. Of course, these quantitative results are based on various debatable assumptions and databases whose reliability is not always guaranteed. For example, we assume that public authorities allow an important use of waste and wood fuels by cement manufacturers, which is criticised by some researchers for public health reasons. However, the main qualitative conclusions seem robust and provide new insights on the much-debated issue of CO₂ leakage and on the ability of BTAs to prevent it.

Annex I:
GEO

Introduction

116. The cement trade has some typical features. First, cement is a heavy product having a low value in relation to its weight, hence very costly to transport. In general, it does not travel more than 200km between the plant and the consumer [ATILH, 2005]. Cement transport is much cheaper by sea than by road. Shipping cement over the Atlantic is cheaper than trucking it 400km [Brockhagen, 2004]. Thus, coastal consumption areas (and consumption areas near borderlines in general) are more sensitive to international competition than inland ones. In the coastal areas of the low competitive countries, domestic firms may have to decrease their profit margin to remain competitive. Secondly, transportation cost is not the only limiting factor for cement trade. Some countries are competitive enough to export much more cement than what they actually do, but they are subjected to a capacity constraint.

117. Therefore, a model designed to cope with cement trade has to focus on geography and on the strategic behaviours of firms when subjected to competition and to their capacity constraint. We built GEO with this state of mind.

118. In GEO, world is modelled as a combination of cement consumption areas – thereafter only referred to as “areas” - on the one hand and producing countries on the other hand. An area is characterized by its geographical position on the globe and its consumption. A producing country is characterized by its variable production cost, its production capacity and the intensity of the competition among its domestic producers. A country is also characterized by the geographical position of its harbours for trade.

119. GEO calculates the minimum transportation cost from every producing country to every consuming area, using fixed and a variable transportation costs for each transportation mode.

120. The goal of a firm is to maximise its profit. We assume it implies that a producing country is ready to sell its production in an area at any price higher than the sum of its variable cost and the transportation cost to this area, subject to a capacity constraint. When the latter is binding, a producing country sells its production in the most profitable areas. The cement price a firm applies in an area is limited by a double price pressure: International pressure from the other producing countries and National pressure from firms of the same producing country.

121. GEO determines under some assumptions, notably on sea and land transportation costs, the world cement market equilibrium. At the disaggregated level, it gives for every area the price of cement and where it comes from. At the aggregated level, it gives for every producing country the production, the capacity utilisation rate and the profit (on variable production cost plus transportation cost), and for every consuming country the average cement price its population faces (which is the weighted sum of the prices in the areas of this country).

122. GEO determines this equilibrium in three steps:

- Firstly, GEO determines the theoretical market area (TMA) of every producing country. The TMA of the USA for example is the set of areas where the USA are the most competitive

country, given transportation costs, *i.e.* where the USA can offer to consumers the best price among all producing countries. In other words, the TMA of the USA is the set of areas where the USA would sell their production if they had no capacity constraint. For every area, GEO computes the profit margin²³ that the most competitive country can keep, taking into account the international pressure.

- Secondly, GEO computes for every area the effective profit margin the most competitive country would keep if it had no capacity constraint taking into account competition between the country's firms (national pressure), modelled through Cournot competition.
- Thirdly, GEO takes into account the capacity constraints of the producing countries. Doing so it determines the real market area (RMA) of every producing country and the profit margin it applies in every area of its RMA, taking into account the international and the national pressure²⁴.

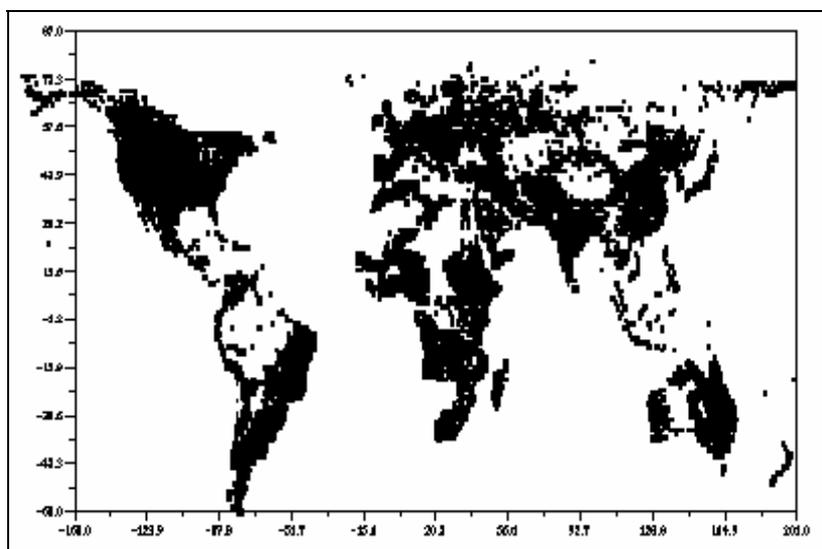
123. We describe below these three steps.

Determination of the theoretical market area (TMA)

Definition of the areas

124. The areas used by GEO are the 1°x 1° squares defined in the EDGAR database [RIVM, 2001], but we subdivided the squares with a high population and dropped the squares where the population is negligible (figure 1)²⁵.

Figure 20: areas of GEO



²³ We mean by profit margin the profit margin on variable production cost plus transportation cost, *i.e.* profit margin = (cement price - variable cost - transportation cost) / (variable cost + transportation cost).

²⁴ To be more realistic, GEO limits the international pressure of a given country to its *competition pressure area* (CPA), notion that will be introduced later.

²⁵ Squares where the population is important (whatever is the criteria) can be divided in sub-squares. In the simulations presented in this report, squares whose cement consumption was more than 0.3Mt in 1998 have been divided so that no square's consumption exceeds 0.3Mt. Finally, GEO works with more than 15 500 areas.

125. For every area, EDGAR gives us its geographical coordinates and its country. We assume that an area's share in the consumption of its country is proportional to its share in the population of its country²⁶:

$$\text{Consumption}(\text{region}) = \text{Consumption}(\text{country}) \cdot \frac{\text{Population}(\text{region})}{\text{Population}(\text{country})}$$

Minimal selling price of a producing country in an area and TMAs

126. To determine to what producing country's TMA an area belongs to, we have to calculate the minimal selling price of every producing country in this area. By minimal selling price of a producing country in an area we mean the sum of its variable production cost and the transportation cost from the producing country to this area. Under the basic assumption that a producing country wants to use its production capacity in full, this is the minimal price it is ready to accept. We consequently have to calculate the transportation cost of a tonne of cement between every producing country and this area.

127. The transportation cost between a producing country and its areas is assumed to be the fixed cost of delivering cement by road. In any other case, cement has to pass through what we name a harbour, which can be a land harbour or a sea harbour. We consider a producing country B and an area a which belongs to $A \neq B$. A has several harbours. $harbourA_i$ is one of these harbours. We calculate the road transportation cost between a and $harbourA_i$ and add the transportation cost between $harbourA_i$ and B . We do that for every harbour of A , so that we have a "transportation cost between a and B " vector. Taking its minimum we get the minimal transportation cost between a and B . Adding the variable production cost of B we get the minimal selling price of B in a .

128. Doing this for every producing country B , we get the "minimal selling price of producing countries in a " vector. a enters the TMA of the producing country whose minimal price is the lowest of this vector. If it and its competitors had no production cap, and taking only into account international pressure (Bertrand competition), the most competitive producing country would apply a price equal to the minimal selling price of the second most competitive country.

129. Doing this work for every area a we determine the TMAs. Then, using the consumption level of the areas, we determine for every producing country the quantity it could sell, and where it could sell, if it and its competitors had no production cap.

Land and Sea harbours definition

130. Every real sea harbour potentially able to trade cement is taken into account in GEO. We have registered 1.590 sea harbours for cement trade in the world [Lloyd, 2004].

131. Land harbours are placed every 25km on the land border of every country. GEO deals with more than 7500 land harbours.

²⁶

GEO have the population of every area from 1998 to 2030. These data have been built using U.N. urban and rural population foresight for all the countries of the world [UN, 2001; UN, 2002]. Data by country have been split into data by area, using area's initial population (from EDGAR) and differentiating the evolution of rural and urban areas.

Road and sea transportation costs

132. Road transportation cost calculation between an area a and a harbour $harbourA_i$ of A rests on a simplification. This cost is the straight distance between a and $harbourA_i$ in km multiplied by the variable road transportation cost in country A , $road(A)$ in €/per tonne km, plus the fixed road transportation cost in this country, $ROAD(A)$ in €/tonne. The estimation of the variable cost takes into account the fact that the distance we measure is the straight one.

133. Road and/or sea transportation cost between $harbourA_i$ and the producing country B comes from the Harbour Matrix. This matrix has been built according to the procedure we describe now.

134. If the junction between $harbourA_i$ and B is by sea, the transportation cost is the sum of the fixed sea transportation cost per tonne, SEA in €/tonne, and the product of the variable sea transportation cost per tonne, sea in €/tonne km, by the junction distance in km. The junction distance between $harbourA_i$ and B is the real distance between $harbourA_i$ and the closest B 's harbour²⁷.

135. If the junction between $harbourA_i$ and B is by road, we consider that the transportation cost is the product of the variable road transportation cost in A by the straight distance between $harbourA_i$ and the closest B 's harbour.

Tableau 1: Extract of the Harbour Matrix

From ⇨ To ↓	Canada	France	United Kingdom
Bordeaux	7800*sea+SEA	0	1050*sea+SEA
Brest	7800*sea+SEA	0	450*sea+SEA
Dunkerque	8600*sea+SEA	0	150*sea+SEA
Le Havre	8300*sea+SEA	0	200*sea+SEA
Marseille	9300*sea+SEA	0	3650*sea+SEA

136. The Harbour Matrix construction requires the calibration of the parameters $ROAD$, $road$, SEA and sea .

137. $ROAD$ and $road$ are two vectors of 47 national road costs, one for every country. According to the road costs in France and Morocco, kindly supplied by LAFARGE, we made a simple linear regression with the GDP per capita to estimate the $ROAD$ and $road$ vectors. When we merge GEO with CEMSIM, we need to know this vector from 1998 to 2030. We assume that, in the business-as-usual scenario, it is constant through time (in €99). When a CO₂ mitigation policy is implemented, road costs in the countries implementing it increase according to the CO₂ content of transport²⁸ and to the CO₂ price.

²⁷ Transportation costs inside the producing country, between cement factories and harbours, are not taken into account. Therefore, transportation costs are under-estimated by GEO. Concerning the solution found to (partially) overcome this bias, see below.

²⁸ We assume that cement is transported by road using 25 tonne trucks. A 25 tonne truck emits 55kgC for 100km, according to [ADEME, 2001]. Therefore, we assume that cement transportation by road emits 2.2kgC per tonne of cement for 100km (55kgC divided by 25 tonne).

Tableau 2: road transportation costs

Country	ROAD (€99)	100*road (€99)
The USA	5.1	9.2
France	3.9	7
RJAN	2.7	4.9
NOAN	0.6	1.1

138. Concerning *SEA* and *sea*, we calibrated them to get the best fit with the cement transportation costs data supplied by LAFARGE for 2002 and 2004. We keep in mind that a huge increase in sea transportation costs took place between 2002 and 2004. We consider, according to specialists that current prices are “reasonable” and will be maintained from now on for many years. Thus, merging GEO and CEMSIM, *SEA* and *sea* are kept constant (in €99) from 2004 to 2030. We keep them constant too between initial time and 2002. Values in 2003 are the average of 2002 and 2004 values.

Tableau 3: Sea transportation costs

	≤ 2002	2003	≥ 2004
<i>sea</i> *1000 (€99)	1.6	2	2.4
<i>SEA</i> (€99)	9.7	12.1	14.6

Internal transportation costs in exporting countries

139. The way we calculate transportation costs leads to under-estimate them. Indeed, we do not take into account the transportation cost of an exporting country from the production site to the harbour. This simplification is inevitable, given the fact that factories are not exactly located inside countries in GEO. To limit the consequences of this simplification we limit the available capacities for export:

140. For every country we differentiate its domestic capacities (built to satisfy domestic consumption) and its export capacities (built in order to export). The first ones are located inside its territory, the second on its land or sea border.

141. We consider, according to specialists, that basic cement does not travel more than 200km by road before it is exported [ATILH, 2005]. Hence only a percentage of the domestic capacity of a country not used for domestic consumption can be exported. Given the importance of road costs, we assume this percentage is the percentage of population living at less than 200km from a sea coast.

142. The capacity of a country available for export is therefore the sum of its domestic capacities not used for domestic consumption and close to a sea coast, and the export capacities. We assume, according to specialist, that there are, until now, no export capacities [LAFARGE, 2004].

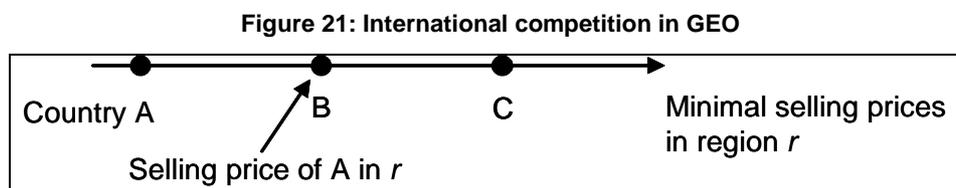
143. Using the percentage of coastal population and not of population close to borderline (which is not available), GEO favours the idea that most of cement trade is done by sea. This idea is confirmed by data and explained by the difference between sea and road transportation costs²⁹.

²⁹

But the use of the coast population percentage is a problem for countries with no access to sea, especially when they are supposed to export because of their low production cost. However, we consider that the quantitative impact of this bias, considering the size of these problematic countries, is negligible.

National pressure: competition among the national firms.

144. Until now we have assumed that the most competitive country in an area keeps the profit margin defined by the international pressure: the maximal profit margin. So its selling price is the minimal selling price of the second most competitive producer.



145. Should we keep on doing that way, it would mean that a country is seen as a cartel of the firms located on its territory, *i.e.* that there is no competition among the firms of a given producing country. This skewed view of reality would have important impacts. Indeed, in an area isolated from international competition, because of its geographical position for example, the domestic producer could keep a huge profit margin: 200, 300% or even more. To avoid that, we introduce in GEO the idea of competition inside a producing country: national competition.

146. We consider that in every area of the TMA of producing country A , a competition “à la Cournot” takes place between the N_A companies located in A . Assuming these companies are identical,

the resulting profit margin with no international pressure is $\mu = \frac{1}{N_A \cdot \varepsilon - 1}$ where ε is the price-elasticity

in the area. Therefore, we make the following assumption: the profit margin of a producing country

(N_A companies) in a area with a price-elasticity ε , is the minimum between $\mu = \frac{1}{N_A \cdot \varepsilon - 1}$ (national

pressure) and the margin defined by the minimal selling price of the second most competitive producing country (international pressure).

147. Being able, in every country, to assess profit margin with no international pressure in 1998 (using variable cost data from CEMSIM-GEO and selling price from [International Cement Review, 1998]) and using price-elasticity from IPTS team, we calculate the theoretical number of companies in every country. The difference between this theoretical number N_{coun} and the observed one traduces the difference between our Cournot oligopoly vision of cement industry and reality, especially the fact that in the real world companies are not identical and are spatially located. In CEMSIM-GEO, numbers of companies are kept constant through time.

Determination of the real market area and of the final profit margin***Real market area***

148. The goal of this part in GEO is to take into account capacity constraints. The constraints of a country are the following:

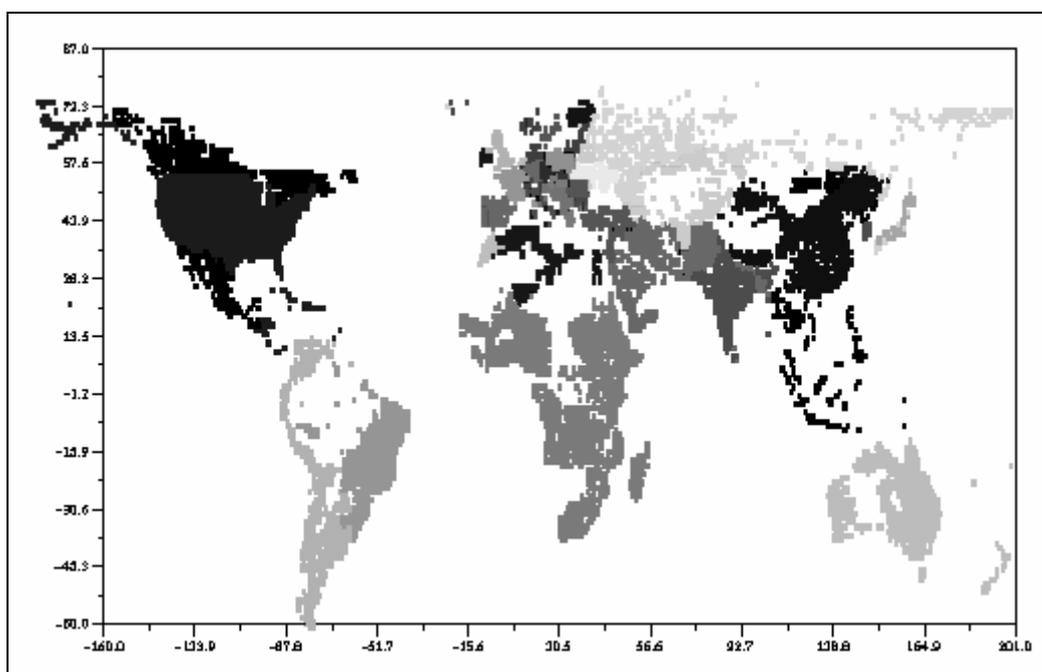
- Production for domestic consumption is limited by the domestic production capacity,

- Export production is limited by the available capacity for export defined before as the sum of export capacities and domestic capacities not used for domestic market and closed to borderline³⁰.

149. We consider that a producing country has under-capacity when it is not able to satisfy the entire consumption of its TMA because of its capacity constraint. Hence, it has to choose the areas where it sells its production and the ones it leaves, given the fact that domestic areas have the priority. As soon as its domestic demand is satisfied, its criterion of decision is its profit maximisation. It sells where the profit margin it can keep is maximal. According to that and if the world capacity is sufficient, there is only one equilibrium taking into account capacity constraints. We developed an algorithm that determines this equilibrium.

150. One of the principles of this algorithm is that the minimal profit margin a producing country with under-capacity is ready to accept is not equal to 0 anymore (*i.e.* its minimal selling price is not anymore the sum of its variable production cost and the transportation cost). Therefore, all the international competition is modified.

Figure 22: RMA from GEO



151. The determination of RMAs gives us for every area where the cement sold comes from and allows us to calculate for every producing country its total sold production and its capacity utilisation rate. Nevertheless, to have access to the cement prices in the areas, to the average national cement prices and to the national profits, we need to introduce what we call the Competition Pressure Areas (CPA).

³⁰

We assume that the cement produced with the shaft technology is of low quality and that it is not traded. Therefore, export capacities do not use this technology and the available capacity for export is defined as the sum of export capacities and domestic capacities not using this technology, not used yet and close to borderline.

Introduction of the competition pressure areas (CPAs)

152. Other assumptions are necessary to simulate selling prices. Otherwise they would be largely under-estimated in comparison with real prices, because the way we have represented competition until now is too harsh³¹.

153. Let's take an example. A and B are two neighbouring countries with the same variable production cost. In every area of A, A is the most competitive country. The selling price is limited by the competition pressure of B. If B has excess capacities, this limit in a given area is the minimal selling price of B in this area (sum of its variable and transportation costs). If B's capacity is saturated, the limit is the previous one increased by the minimal margin B is ready to accept. This is true wherever in A. But the idea that B is able to provide cement instantaneously in any area of A as soon as A's selling price is superior to B's minimal selling price is not realistic. Such an ability of reaction is not possible, because it would be extremely expensive. However, it is what this worldwide B pressure presupposes: B's threat is credible all over the world.

154. That's why GEO considers that:

- A country using its domestic capacities in full (for domestic consumption or for export) does not keep price pressure over its own territory;
- A country with domestic overcapacities keeps price pressure all over its own territory;
- A country with no capacities available for export, or with capacities available for export but used in full, does not keep price pressure out of its territory;
- A country with capacities available for export not used in full keeps price pressure out of its territory in a subset of its RMA which we label its competition pressure area (CPA). The CPA of a given country is defined by the fact that:
 - The total consumption of its CPA equals its available capacity for export not used yet;
 - It only includes areas where it is the second most competitive country;
 - If its export pressure capacity is not sufficient for all these areas the country chooses the areas where the difference between its minimal selling price and the current supplier's minimal price is the smallest. This criterion of distinction seems to be the most realistic one. This price pressure capacity is focused on the areas where, being close to the minimal selling price of the seller, a producer has more hope to "do business".

155. Determining CPAs allows us to calculate the selling prices of every producing country in every area of its RMA. Consequently, GEO can calculate the profit of every producing country and the average domestic cement price in every (consuming) country.

Calibration of GEO

156. The calibration of GEO relies on the introduction, in the transportation costs between two countries i and j , of a parameter labelled $NTB_{i \rightarrow j}$ representing the Non Transport Barriers between these countries. The set of parameters $(NTB_{i \rightarrow j})_{\substack{i=1 \dots N \\ j=1 \dots N}}$ is determined using national variable production costs in 1998 from CEMSIM, transportation costs in 1998 extrapolated from data in 2004 supplied by LAFARGE and bilateral trade data in 1998, from OECD series C.

³¹ Another reason is that transportation costs of export production from production sites to harbours are not taken into account as we already said.

Annex II:
GEO CAPACITY PLANNING (GEOCP)

157. In GEO, as in the real world, cement manufacturers compete on the international market with two key parameters: their production cost and their production capacity. Therefore, a good modelling of the world cement industry has to represent the decision of investment in new capacities. This is especially relevant because one of the possible effects of the implementation of environmental policies is the building, in the countries that do not implement these policies, of capacities designed to export towards the ones that do implement them.

158. In CEMSIM-GEO, the behaviour of investors is modelled through GEO capacity planning, GEOcp, a modified version of GEO.

GEOcp: Principle

159. Between times t and $t+1$, every producing country has the possibility to built new capacities. To take its decision, it foresees the world at time $t+1$ and decides to supply the most profitable areas where it will be the most cost-competitive country. If it foresees that its existing capacities will not be fully used, it does not build new capacities. If it foresees that its existing capacities will be fully used, it builds new capacities to supply the areas where the price it could keep is high enough to cover not only its variable production cost but also its construction cost.

160. In this section, we use two examples in order to explicit the principle of GEOcp. In these examples, we only consider the interactions between two countries, country 1 and country 2. In order to simplify the understanding of GEOcp, these countries are assumed to be two islands. Each country is characterized by a variable production cost CV (which is the cost of producing one tonne of cement when the plant has already been constructed), a fixed production cost CF (which is the cost of building a plant, annualised trough its lifetime), a production capacity CAP and a cement consumption CON homogeneously spread. In these examples, we assume that all the capacities are able to produce to export. However, we keep on distinguishing the domestic capacities and the export capacities. At the initial time, there are no export capacities.

Example 1: Building of export capacities

161. At time t , $CV1$ and $CV2$ are such that country 1 imports cement from country 2. $CAP2 > CON2$ and $CAP1 \geq CON1$. The cement quantity that country 2 exports is not limited by the growth of the transportation costs (the more country 2 exports, the deeper it has to enter inside country 1's territory) but by its capacity $CAP2$.

162. The countries have now to decide if they invest in new capacities for time $t+1$. We assume the production costs, the transportation costs and the consumptions remain constant between t and $t+1$. Moreover, no capacities of the country 2 retire. Foreseeing $t+1$, is country 2 going to build new capacities to export to country 1? Given the exports of country 2 at time t and the fact that these exports were limited by its production capacity and not by its cost-competitiveness, it seems natural that it will. However, country 2 has to take into account its fixed production cost $CF2$. Its real variable production cost is not $CV2$ but $CV2+CF2$ when the production of a tonne of cement requires the building of a new capacity.

Therefore, country 2 builds a new capacity in order to export cement to an area of country 1 if the price it foresees it could keep is higher than CV_2+CF_2+CT , with CT the transportation cost from country 2 to this area.

163. To keep a price higher than CV_2+CF_2+CT in an area of country 1 does not necessarily mean for country 2 that the sum CV_2+CF_2+CT has to be lower than CV_1 . Country 2 could keep such a high price if country 1 lacks domestic capacities a time $t+1$, if it has to build a new capacity to supply this area (*i.e.* this area is not a priority for country 1) and if $CV_1+CF_1 > CV_2+CF_2+CT$.

164. Whatever, country 2 builds export capacities only if it foresees that its domestic capacities which are not used to satisfy the domestic demand (*i.e.* its domestic overcapacities) will be fully used to export at time $t+1$. Country 2 foresees to supply the most profitable areas of country 1 with its domestic overcapacities (production cost CV_2) and then decide to build, or not to build, export capacities (production cost CV_2+CF_2) for the other areas of country 1.

Remarks

165. Until now, there are no export capacities in the real world: cement exports come from countries with domestic overcapacities. We may distinguish three different origins for the existence of domestic overcapacities:

- the inertia of the capacities in the countries whose consumption decreases (Japan, some European countries for example);
- a bad forecast of the evolution of the domestic consumption, which can be due to an economic crisis that suddenly makes the consumption drop (Asian countries after 1997 for example);
- the fact that the firms build bigger plants than what they exactly need, expecting consumption growth (Turkey for example) or the retirement of old capacities in a the very short term.

166. It seems that most of the current exports come from the domestic overcapacities of country with a growing consumption: planned domestic overcapacities.

167. Following the GEOcp analysis, the absence of export capacities has two reasons:

- It is difficult to build capacities in order to export to countries with domestic overcapacities (and most of the countries have some). Thus, the European countries with high production costs are protected from the building of export capacities by their domestic overcapacities. For example, to build in Turkey a capacity to supply cement in Marseille would be possible if $CV_{turkey}+CF_{turkey}+CT_{turkey-marseille} < CV_{france}$.
- A low production cost country builds export capacities only if it already exports its entire domestic overcapacities. But low production cost countries generally have a rapidly growing consumption, and so have huge planned domestic overcapacities.

168. It is worth noting that the implementation of CO_2 policies could modify the current situation. For example, the increase in the European production costs would help Turkey firstly to fully used its domestic overcapacities and then, maybe, to build capacities to export in Marseille.

Example 2: Building of domestic capacities

169. At time t , CV_1 and CV_2 are so that there is no trade between the two countries. The production costs, the transportations costs and the consumptions remain constant between t and $t+1$. But some

capacities of country 1 retire: if it does not build new capacities, it will not be able to satisfy its entire domestic consumption $CON1$. Foreseeing $t+1$, is country 1 going to build new domestic capacities? Given the fact that country 1 does not import cement at time t , it seems natural that it will. But, one more time, the country which builds new capacities has to take into account its fixed production cost CF .

170. Country 1 foresees to use at time $t+1$ its existing capacities to supply its most profitable areas³². For the remaining areas, it has to build new capacities. Its variable production cost in these areas is $CV1+CF1$. This cost is in competition with the variable production cost of country 2: $CV2+CT$ for country 2's existing capacities, $CV2+CF2+CT$ for country's capacities that have to be built.

171. If country 2 has a huge domestic overcapacities, country 1 builds new capacities for the remaining areas where $CV1+CF1 < CV2+CT$.

172. If country 2 has no domestic overcapacities ($CON2=CAP2$), country 1 builds new domestic capacities for the remaining areas where $CV1+CF1 < CV2+CF2+CT$.

173. If country 2 has few domestic overcapacities, it foresees to use this overcapacity at time $t+1$ to supply cement in the most profitable remaining areas of country 1 where $CV2+CT < CV1+CF1$. For the rest of the remaining areas, country 1 builds domestic capacities when $CV1+CF1 < CV2+CF2+CT$, and country 2 builds export capacities when $CV2+CF2+CT < CV1+CF1$.

174. Thus, a country, even not a very high production cost country, can be lead not to renew its domestic capacities for its areas where the competition is hard. With the implementation of a CO_2 policy, such a situation could frequently appear.

GEOcp: details

175. In CEMSIM-GEO, most of the parameters evolve between time t and $t+1$:

- Consumption levels are influenced by GDP, population or prices;
- Old capacities retire;
- The fluctuation of the energy prices, the modification of the technological portfolio through retrofitting options or the implementation of environmental policies have an impact on the productions costs;
- Transportations costs evolve;
- ...

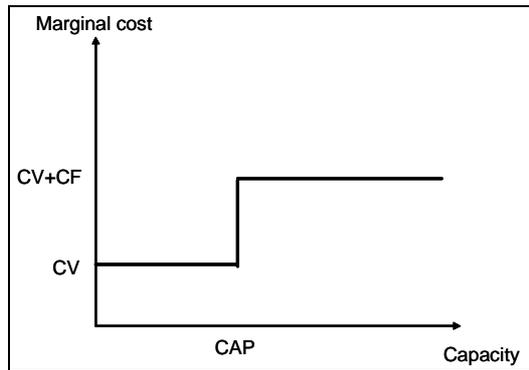
176. At time t , every country foresees its consumption, its production costs and its production capacity at time $t+1$. These forecasts are assumed to be shared among all the producers of the world. They are the inputs of GEOcp. GEOcp determines the equilibrium resulting from these inputs.

177. The algorithm of GEOcp is a modified version of the algorithm of GEO. A country competes on the world cement market with its variable production cost CV as long as its existing capacities (domestic and export capacities) are not fully used. When they are, it competes with capacities it has to build, hence with a variable production cost that takes into account the construction costs: $CV+CF$.

178. The supply curve of a country in GEOcp is:

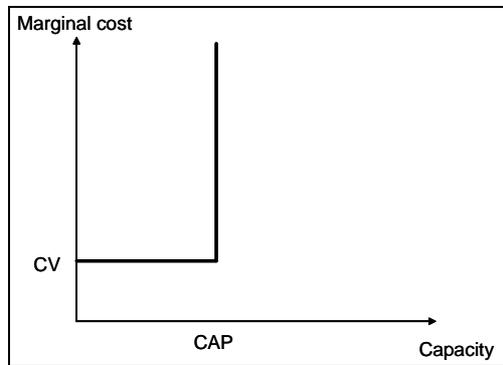
³² This decision criteria has been chosen in order to be coherent with GEO.

Figure 23: Supply curve in GEOcp



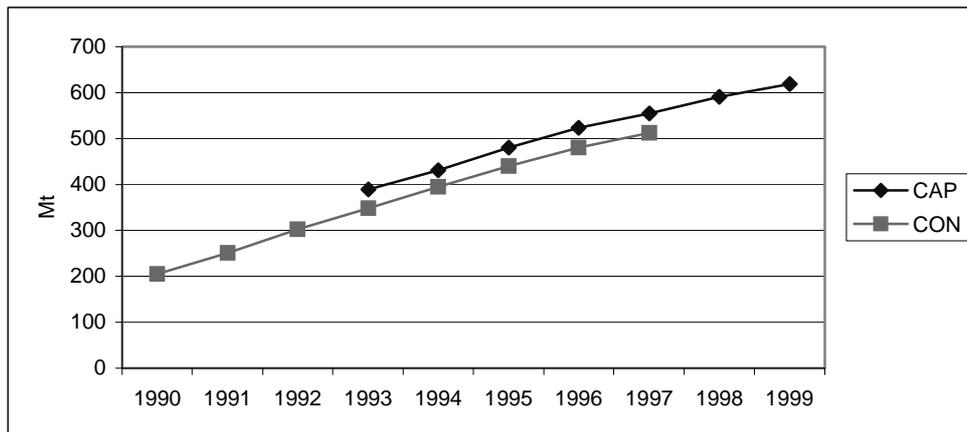
whereas it was, in GEO:

Figure 24: Supply curve in GEO



179. In the real world, the cement capacity of a country does not follow exactly the production but evolves as shown below:

Figure 25: Chinese consumption and capacity



180. A new factory is a consequent investment hence building a new one is an important decision. When such a decision is taken, obviously not every year, the size of the new factory is calculated to fit with the expected production in many years, let say $2 \cdot Y$ years, taking into account the retirement during this time. All the cement companies of a country doing the same, the capacity of a country at time $t+1$ is

sufficient, taking into account retirement, to satisfy its consumption in $t+1+Y$, $Y>0$, taking into account the retirement of old capacities between $t+1$ and $t+1+Y$.

181. This phenomenon is critical: as we have already noticed, current exports come from these planned domestic overcapacities that have to be used, as long as the selling price is bigger than the variable production cost. In order to model the planned overcapacities phenomenon, countries in our model base their decision at time t on their expected production and remaining capacities not at time $t+1$ but at time $t+1+Y$. We assume Y is the same for all the countries in the world. Analysing real data from countries with growing consumption, we finally take $Y=1$.

182. It implies that a country, with a constant annual consumption growth rate A , has planned overcapacities that represent $100 \cdot \left(\frac{(1+A)^Y}{(1-1/TCLT)^Y} - 1 \right)$ per cent of its consumption, with $TCLT$ the technical lifetime of machines³³. For example, a country with a stagnating demand has an overcapacity which accounts for around 3% of its consumption³⁴. The overcapacity of a country with a demand growing by 5% every year accounts for 8% of its consumption.

³³ $CAP(t) \cdot \left(1 - \frac{1}{TCLT}\right)^Y = CON(t+Y) = CON(t) \cdot (1+A)^Y$; $TCLT=35$ years.

³⁴ We notice that such an overcapacity for a country with a stagnating demand is coherent with the fact that the plants have not to be used with a 100% utilisation rate.

Annex III:
CEMSIM-GEO

Introduction

183. The analysis of the competitiveness impacts of CO₂ mitigation policies in the cement sector required a deep collaboration between the Institute for Prospective Technological Studies (IPTS) and the International Centre on Environment and Development (CIRED). The fruit of this collaboration is CEMSIM-GEO, a recursive world cement industry that merges the IPTS world cement model CEMSIM and the world competition model developed by CIRED for this purpose, GEO.

184. CEMSIM-GEO aims at giving, for different CO₂ mitigation policies, a vision of the world cement sector between 1998 and 2030. Countries of the world are grouped according to the 47 countries of the POLES nomenclature. The model operates with a succession of modules: cement consumption, production costs (notably energy and emission costs), international competition, technology dynamics and investment decision.

185. As in the original CEMSIM IPTS model, national consumption trends are exogenously driven by the “intensity of use hypothesis”. An inverted U-shape curve explains the time evolution of cement intensity per unit of GDP. The demand curve for cement is assumed isoelastic, with a price-elasticity of 0.2, a value close to that estimated by La Cour and Mollgaard ([La Cour and Mollgaard, 2002], cited and used by [IEA, 2004]).

186. International competition is represented through the world competition model GEO and the investment decision process through GEOcp.

187. As in the original CEMSIM IPTS model, production costs and technology dynamics modules distinguish seven technologies characterized by energy, material and labour consumption, an investment cost and a set of retrofitting options.

188. The main exogenous variables of the model are population, GDP, electricity and primary fuel prices taken from POLES³⁵. Prices of other fuels (waste and wood fuels, petroleum coke) come from a calibration work³⁶. The techno-economic characteristics of the cement industry have been collected by the IPTS team and are modified through the recursive process. For the calibration of the model, we use 1998 and 1997 real data on consumption, production capacity or energy demand [CEMBUREAU, 1999b; CEMBUREAU, 2002]. The model is then recursively run with a yearly step.

189. Impacts of climate policy on the cement industry are studied through the introduction of a CO₂ tax (equivalent to an auctioned tradable CO₂ allowances system). The CO₂ value triggers different mechanisms: reduction of cement demand due to the increase in production costs and hence in prices; substitution between clinker (CO₂ intensive product) and added materials in cement composition;

³⁵ The LEPII-EPE provided us with regional (47 POLES regions) energy prices data, depending on the CO₂ policy simulated. These prices are related to the demand from industry, transport, households...

³⁶ Petroleum coke and waste and wood fuels prices are indexed on primary fuel prices.

substitution between high and low carbon fuels (coal, oil, coke; gas, waste and wood fuels); retrofitting of CO₂ intensive to low CO₂ technologies; changes in technological designs for new plants. Moreover, CEMSIM-GEO can account for the fact that regional climate policies may change the competition conditions and consequently impact the equilibrium among producing countries on the world cement market.

190. In the following section we give an overview of the cement industry, for the reader to understand the way the cement industry is modelled in CEMSIM. Then, we deeply describe the CEMSIM-GEO model

Cement industry overview

191. This section is a re-organised version of the cement industry overview section in [Szabo *et al.*, 2003].

Production process

192. Cement manufacturing consists in three main steps. Raw materials are first mined, ground and homogenized. Then they are burned at high temperature: calcination and clinkerization take place to produce clinker. Finally, clinker is ground or milled and mixed with additional materials to produce cement. We shortly describe below these various steps.

Mining and preparation of raw materials

193. The calcium oxides required for the central step, clinkerization, is provided by natural occurring calcareous deposits such as limestone, clay or chalk. These materials are the most common raw materials. They can be found in all regions of the world. The raw materials have to be homogenized, ground and crushed to the required fineness. Some other materials are required for the clinkerization process: silica, iron oxide and alumina that are found in various ores and minerals, such as sand, shale, clay and iron ore. Power station ash, blast furnace slag, and other process residues can also be used as partial replacements for the natural raw materials.

194. Around two tonnes of raw materials are required for the production of one tonne of clinker. The energy consumption in this step is mainly electricity consumption, between 25-30kWh/tonne of clinker [EC, 2000].

Clinker production

195. The prepared raw material is burned at high temperature. At temperature above 900°C, the calcination of the calcium carbonate takes place, producing the calcium oxide required for the clinkerization step. There is CO₂ emission not only from the fuel combustion, but from the process itself. With the CO₂ emission, the raw material loses more than one third of its original weight.

196. The clinkerization takes place at 1300-1450°C where parts of the material are liquid and stick together to form nodules (clinker). Formation of alite (tricalcium silicate) takes place at this step. Alite is one of the most important fraction of the clinker, as this determines the hardening property of the cement. The material then must be cooled rapidly, because with slow cooling high portion of alite could be lost.

197. Basically two types of kiln are used for the pyro-processing of the raw material: vertical kilns (shaft kilns), and rotary kilns. Rotary kiln is a tube with a diameter of up to 6 meters, with a length of 10-20 times its diameter in case of short kiln, and 32-35 times in case of long kilns. The kilns are installed with a slope of 3-4 degrees with respect to the horizontal and are rotating slowly to move the raw material

towards the direction of the flame to the lower end of the kiln. The different kiln types will be introduced later. The energy consumption for every kiln is given in the next section.

Finish grinding

198. After cooling, clinker can be stored in closed silos or in other types of storage devices. To produce cement, clinker should undergo grinding to the required fineness. Additional materials, such as gypsum, pozzolona, fly ash and burnt shale are then added to the material. The usual equipments are ball mills and rolling press together with separators. Portland cement contains at least 95% of clinker, while other cements (Blended Portland, blast furnace and pozzolanic cement) contain less, but usually over 65%. The energy consumed is mainly electricity, between 30-55Wh/tonne of clinker [EC, 2000].

Kiln technologies

Technologies selected

199. Seven kiln types for clinker production (step 2) were chosen to be included in the model³⁷.

- Wet rotary kiln
- Semi-wet rotary kiln
- Semi-dry rotary kiln
- Dry long rotary kiln
- Dry rotary kiln with pre-heater
- Dry rotary kiln with pre-heater and pre-calciner
- Shaft kiln

200. First we shortly describe these technologies and then give for each kiln the energy consumption, electric or non-electric.

Wet rotary kiln

201. If the water content of the raw material is high (between 15-25%, e.g. chalk) usually wet slurry is produced to feed the kiln. The kiln food contains around 38% water. The advantage of the process is to have more homogeneous meal for the kiln and less electricity consumption for the grinding. The disadvantage is that water must be evaporated in the kiln, which results in much higher total energy consumption. In places where water content is high (GB, Belgium) this process is still an existing technology of clinker making.

Semi-wet rotary kiln

202. In the semi-wet process, the wet raw material is processed in filter presses after homogenising, resulting in lower moisture content. It is an improvement of the wet process, and mainly used for retrofitting the existing wet kilns. The process reduces significantly energy consumption compared to the wet process.

³⁷ We do not take into account the fluidised bed kiln, the advanced grinding technologies or the use of new materials (mineral polymers). Indeed, we assume that no large-scale commercial application is anticipated in 30 years time for these emerging technologies.

Semi-dry rotary kiln

203. In the semi-dry rotary kiln, moisture content is reduced by using waste heat recovered from the kiln. Then this dried meal is introduced into the kiln.

Dry long kilns

204. This group includes long dry kilns (*e.g.* fed by dry raw material) without pre-heater or with basic pre-heater (shaft pre-heater or one stage cyclone pre-heater). These kilns still have high energy consumption because the pre-heater is missing or not as efficient as the new multi-staged cyclone pre-heaters.

Dry kilns with pre-heater

205. This group includes kilns with multi-staged (4-6) cyclone pre-heaters. The raw material goes down by gravity through the cyclones, placed above each others in towers that can be more than 100 meters high, where each following cyclone has higher temperature. Earlier in the 1970's 4 stages pre-heater kiln was the most wide-spread installation. Now, 5 or 6 stages pre-heater kilns are constructed.

206. As one part of the calcinations process already takes place in the pre-heater, the length of the kiln and therefore the energy consumption is reduced significantly. One disadvantage is that alkalis (that reduce cement quality and can block the operation of the pre-heater) can build-up and collect in the pre-heater. Hence alkalis should be separated from the exhaust gas, what usually leads to extra energy use. However, the energy consumption of kilns with pre-heaters is much smaller than the previous categories.

Dry kilns with pre-heater and pre-calciner

207. In this process an extra combustion chamber is installed between the pre-heater and the kiln. This pre-calciner chamber consumes 60% of the fuel used in the kiln, and 80-90% of the calcination takes place here. There are many advantages of the pre-calcinating process. It further decreases energy consumption by 8-11%. Secondly combustion in this chamber is at lower temperature as in the kiln so lower grade fuel can be used. Finally kiln length can be further decreased and therefore the capacity of the kiln increased.

Shaft kilns

208. Shaft kilns are vertical installations where raw material, mixed with the fuel, is travelling from the top to the bottom by gravity. The same phases are present in this process (calcinations, clinkerization and cooling). But the complete combustion (and so clinker quality) is highly dependent on the homogenisation of raw material and fuel and on the air supply, blown from the bottom. In theory, shaft kilns can almost reach the energy efficiency of the rotary kilns but its not the case in practice. Their usual size is low and many of them are fully-hand operated.

209. Significant number of shaft kilns can only be found in developing countries, where lack of infrastructures, lack of capital or other factors makes them viable.

*Kiln energy consumption***Tableau 4: Kiln energy consumption**

	Wet	Semi Wet	Semi Dry	Dry Long	Dry Preheater	Dry Precalciner	Shaft
Specific heat consumption GJ/t clinker	5.0-7.5	3.4-4.	3.2-3.9	3.6-4.5	3.1-3.5	3.1-3.2	3.7-6.6
Specific electric consumption MWh/t clinker	0.025	0.03	0.03	0.025	0.022	0.022	0.03

Source: [EC,2000 ; CEMBUREAU, 1999a]

Investment costs

210. The cement industry is a very capital intensive industry. The following table indicates the difference amongst the greenfield total investment costs (for the three production steps) for the different technologies selected.

Tableau 5: Investment costs

Technology	Relative Investment cost
Wet	80%
Semi Wet	100%
Semi Dry	100%
Dry Long	80%
Dry Preheater	100-115%
Dry Precalciner	95-100%
Shaft	n.a.

Source: [CEMBUREAU, 1999a]

Retrofitting options

211. One of the most important mechanisms in the model is the retrofitting option among technologies. Retrofitting in the model means the transformation of one technology to another, if it is technologically feasible and economically rational.

212. Technological feasibility is determined according to previous studies [EC, 2000; Hendriks *et al.*, 2000]. The possible retrofit options are the following:

Tableau 6: Retrofitting options

From/To	Semi Wet	Semi Dry	Dry Preheater	Dry Precalciner
Wet	✓	✓	✓	✓
Semi Wet		✓	✓	✓
Semi Dry			✓	✓
Dry Long			✓	✓
Dry Preheater				✓

213. Both investment and variable costs are considered to determine the economic worthiness of the retrofit option. Retrofitting investment costs compared to an “average” greenfield investment cost (which would score 100% in the investment costs table) are:

Tableau 7: Retrofitting costs

From/To	Semi Wet	Semi Dry	Dry Preheater	Dry Precalciner
Wet	3%	5%	37%	55%
Semi Wet		5%	37%	55%
Semi Dry			10%	15%
Dry Long			10%	15%
Dry Preheater				14%

Source: [IEA, 1999; Hendriks et al, 2000]

214. The table shows that there is high premium on retrofitting compared to new investment, where it is available. Thus there is high incentive for the industry to retrofit aged capacities instead of investing in new capacities. This process is intensified with increasing energy prices, as the cost advantage of these new capacities will increase.

CEMSIM-GEO overview

215. In this section, we describe the CEMSIM-GEO model which merges the spatial model GEO, developed by CIRED, and a somewhat modified version of CEMSIM, the model developed by the IPTS. CEMSIM-GEO operates with the succession of 6 modules:

- The consumption module. It is a perfect reproduction of the consumption module from CEMSIM.
- The variable production cost module. It is a somewhat modified version of the production costs, energy consumption and emissions modules of CEMSIM. The modifications concern the treatment of non primary fuels and of cement clinker content, which have been endogeneized.
- The international competition module. It uses the original tool we have already described, GEO. Moreover, the way technological choices are modelled is somewhat different from CEMSIM.
- The technological dynamics module. The retiring and the retrofitting procedure are exactly the ones developed by the IPTS team in CEMSIM.
- The investment decision module. The amount of new capacities built in every country is calculated using the modified version of GEO, GEOcp (GEO capacity planning). The

technological choice for the new capacities use the procedure developed by the IPTS team in CEMSIM.

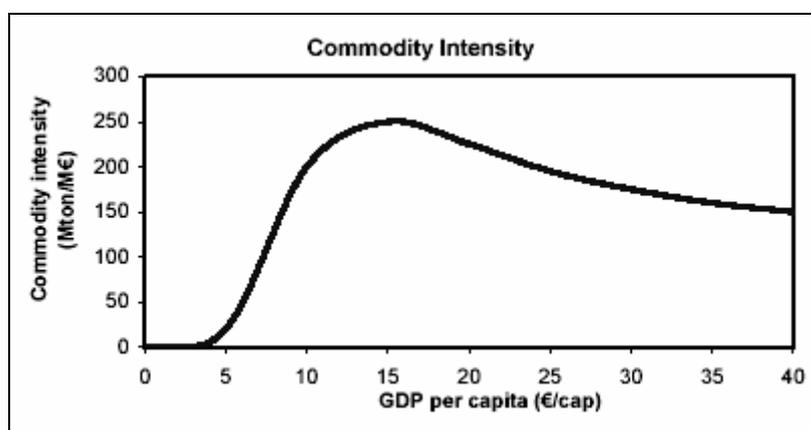
Consumption module

216. This section comes from [Szabo *et al.*, 2003].

217. In a country, the consumption of cement of a country is calculated in the model using the commodity intensity (commodity consumption per unit of GDP and per capita), GDP per capita and population forecasts. GDP per capita forecasts are the same as in POLES. Population forecasts come from [UN, 2001 : UN, 2002].

218. Empirical research showed that the commodity intensity can be often described as a function of the national per capita income. This function has been determined empirically and varies among countries and materials, but its general shape follows an inverse U-shaped curve [Van Vuuren, 1999].

Figure 26: Commodity intensity curve



Each country has its own pattern of consumption growth, represented by the equation:

$$PGCON_{t,coun} = e^{\left(K_{coun} + \ln(PGCON_{t-1,coun}) + SHPA_{coun} \cdot \left(\frac{1}{GDPPOP_{t,coun}} - \frac{1}{GDPPOP_{t-1,coun}} \right) + SHPB_{coun} \cdot (GDPPOP_{t,coun} - GDPPOP_{t-1,coun}) \right)}$$

where K_{coun} , $SHPA_{coun}$ and $SHPB_{coun}$ are the shape parameters of the curve and $GDPPOP$ is the GDP per capita (thousand €/inhabitants). Values of the shape parameters have been calibrated by the IPTS team to get the best fit to the actual data on clinker consumption to the last 15-20 years, depending on the country.

219. Cement demand for the modelling period is then calculated using GDP per capita and population (POP) forecasts with the commodity intensity:

$$CON_{t,coun} = CON_{t-1,coun} \cdot \left(\frac{PGCON_{t,coun}}{PGCON_{t-1,coun}} \right) \cdot \left(\frac{GDPPOP_{t,coun}}{GDPPOP_{t-1,coun}} \right) \cdot \left(\frac{POP_{t,coun}}{POP_{t-1,coun}} \right) \cdot \left(\frac{DOMPRICE_{t-1,coun}}{DOMPRICE_{t-2,coun}} \right)^{PRE_{coun}}$$

220. $DOMPRICE_{t-1,coun}$ is the average cement price at time t-1 in country coun and PRE_{coun} is the price elasticity³⁸ in this country. By construction, the price effect has a one year delay in the model, which is not unrealistic given the inertia of the building sector.

Variable production cost module

221. Except the endogeneisation of fuel choices that are not primary fuels, *i.e.* wood and waste fuels and coke, and the decision on national clinker rates in cement, the work presented in this section has been done by the IPTS team [Szabo *et al.*, 2003].

222. The goal of this module is to determine, for every country, the variable production cost of each technology to produce one tonne of cement. These technological variable production costs will be used in the technological dynamics module where retrofitting options take place. Moreover, from its technological costs and its clinker rate, each country calculates its average cement variable production cost. This parameter is determining in the competition between countries represented through GEO (see Annex I).

223. We distinguish the seven technologies already described and use in this module their characteristics on energy, material and labour consumption.

224. The way the variable production costs by technology of a tonne of clinker are calculated ($CV_{t,coun,tech}^{clink}$) is presented in the first subsection. In the following one, we expose how the clinker rate applied by the firms of a country is chosen ($CKrate_{t,coun}$). Finally, we present the calculation of the national variable production costs of a tonne of cement by technology ($CV_{t,coun,tech}$) and of the national average variable production costs of a tonne of cement ($CV_{t,coun}$).

Variable cost of clinker

225. The variable production cost of a tonne of clinker is the sum of:

- The variable operation and maintenance cost $CVOM_{coun,tech}^{clink}$ that covers the labour costs of the clinker production. It is a multiplication of hourly wages in country coun and the labour requirement in hour/tonne of clinker for the technology tech.
- The raw material price RMP . We assume it is the same in all countries for every technology and at any time between initial and final time. It is set according to the techno-economic database provided by [ECOFYS, 2002].
- The variable energy cost $CVE_{t,coun,tech}^{clink}$.
- The variable CO₂ emission cost $CVEM_{t,coun,tech}^{clink}$.

³⁸ IPTS team did not find in literature analysis a study that gives cement price elasticities. They tried for some European countries and US a regression estimation, but at the end nothing was significant. So they finally, and until now, assume a quite rigid market: $PRE_{coun}=0.2$ for every country.

Variable energy cost

226. Energy consumption is divided into electricity and fuel consumption. By fuel or non-electric energy, we mean the primary fuels (coal, gas and oil), coke and “waste and wood fuels” (WWF).

227. $SELED_{t,coun,tech}$ and $SNELD_{t,coun,tech}$ are respectively the specific electricity and non-electric energy consumption per tonne of clinker at time t in country coun with technology tech. Energy efficiency improvement are modelled by making a weighted sum of the specific energy demands of the new built capacities, $NWSELED_{t,tech}$ and $NWSNELD_{t,tech}$, and of the specific energy demands of the remaining park from t-1 taking into account retrofitting process, $SELED_{t-1,tech}$ and $SNELD_{t-1,tech}$, by the production capacities.

$$SELED_{t,coun,tech} = \frac{NWSELED_{t,tech} \cdot NWBCAP_{t,coun,tech} + SELED_{t-1,coun,tech} \cdot CAP_{t,coun,tech}^{w/o}}{CAP_{t,coun,tech}}$$

$$SNELD_{t,coun,tech} = \frac{NWSNELD_{t,tech} \cdot NWBCAP_{t,coun,tech} + SNELD_{t-1,coun,tech} \cdot CAP_{t,coun,tech}^{w/o}}{CAP_{t,coun,tech}}$$

228. $NWBCAP_{t,coun,tech}$ is the new clinker capacity built between t-1 and t, and $CAP_{t,coun,tech}^{w/o}$ is the clinker capacity at time t if no new capacity had been built between t-1 and t (see module Capacity planning).

229. We assume the energetic performance of new capacities increase every year by 0.5%. The specific energy consumptions of new capacities at initial time are taken from the available literature and statistics [IEA, 1999, 2002a, 2002b; Hendriks et al, 2000].

230. The variable electric energy cost is consequently known: $ELEP_{t,coun} \cdot SELED_{t,coun,tech}$, where $ELEP_{t,coun}$ is the price electricity in coun at time t (exogenous input from POLES).

231. The calculation of the variable cost coming from fuel combustion requires the knowledge of the average fuel price (where fuel prices are weighted by their shares in total fuel consumption) at time t in country coun, $AVFP_{t,coun}$, so

$$CVE_{t,coun,tech}^{clink} = AVFP_{t,coun} \cdot SNELD_{t,coun,tech} + ELEP_{t,coun} \cdot SELED_{t,coun,tech}$$

232. In every country we have to calculate the share of each fuel in the clinker production. These shares are driven by the fuel prices and the inertia of the system. Primary fuel prices ($FP_{t,coun,coal}$, $FP_{t,coun,gas}$ and $FP_{t,coun,oil}$) are exogenous inputs coming from POLES. Coke and WWF prices come from a calibration work:

- WWF price in a country is indexed on the average primary fuel price in this country
 $FP_{t,coun,coke} = A_{coun} \cdot AVprFP_{t,coun}$

- Coke price in a country is indexed on the average primary fuel price in this country

$$FP_{t,coun,coke} = B_{coun} \cdot AVprFP_{t,coun}$$

233. The two parameters A_{coun} and B_{coun} have been calibrated so that predictions of the energy module running from 1980 to 1997 fit on observed fuel shares in 1997.

234. From the data on fuel prices, the module calculates the fuel shares following the Putty-Clay procedure described below.

235. At time t , a country producing $PRO_{t,coun}$ with the different technologies ($PRO_{t,coun,tech}$) consume during the all year $NELDEM_{t,coun}$ TOE of non-electric energy:

$$NELDEM_{t,coun} = \sum_{tech} NELDEM_{t,coun,tech} = \sum_{tech} (PRO_{t,coun,tech} \cdot SNELD_{t,coun,tech})$$

236. With the calculation of fuel demand at time t , new additional demand is determined which should be satisfied by fuels:

$$NWFD_{t,coun} = NELDEM_{t,coun} - NELDEM_{t-1,coun}$$

237. The demand of the fuel $fuel$, $FDEM_{t,coun,fuel}$, is given by

$$\begin{aligned} FDEM_{t,coun,fuel} = \\ \text{If } NWFD_{t,coun} > 0 \\ \text{Then } FDEM_{t,coun,fuel} &= FDEM_{t-1,coun,fuel} \cdot FSH_{t,coun,fuel} + NWFD_{t,coun} \cdot FSHNWD_{t,coun,fuel} \\ \text{Else } FDEM_{t,coun,fuel} &= FDEM_{t,coun,fuel} \cdot FSH_{t,coun,fuel} \end{aligned}$$

238. The fuel shares in the new additional fuel demand are:

$$FSHNWD_{t,coun,prfuel} = \frac{FC_{t,coun,fuel}^{-EH_{coun}}}{\sum_{fuel} FC_{t,coun,fuel}^{-EH_{coun}}}$$

239. The shares used to satisfy the previous fuel demand are:

$$FSH_{t,coun,prfuel} = \frac{FSH_{t-1,coun,fuel} \cdot FC_{t,coun,fuel}^{-FSHEL_{coun}}}{\sum_{fuel} FSH_{t-1,coun,fuel} \cdot FC_{t,coun,fuel}^{-FSHEL_{coun}}}$$

240. These shares depend on the fuel utilisation costs:

$$FC_{t,coun,fuel} = \frac{FP_{t,coun,fuel} + PC_{t,coun} \cdot CC_{fuel} \cdot \frac{44}{12}}{AFE_{coun,fuel}}$$

where $FP_{t,coun,fuel}$ is the fuel price (€99/TOE) from POLES and from the calibration work, $AFE_{coun,fuel}$ the fuel average efficiency, $PC_{t,coun}$ the CO₂ price and CC_{fuel} the carbon content of fuels [MATE, 2002].

Tableau 8: Fuels carbon content

CC_{COAL}	1.08 tC/toe
CC_{GAS}	0.65 tC/toe
CC_{OIL}	0.84 tC/toe
CC_{COKE}	1.1 tC/toe
CC_{WWF}	0 tC/toe

And finally,

$$AVFP_{t,coun} = \sum_{fuel} \frac{FDEM_{t,coun,fuel}}{NELDEM_{t,coun}} \cdot \frac{FP_{t,coun,prfuel}}{AFE_{coun,prfuel}}$$

Variable CO₂ emission cost

241. We consider that there is in clinker production two sources of emissions: emissions from fuel combustion and emission from the decarbonation of calcium carbonate during the clinker burning.

242. $EFFC_{t,coun,tech}$ is the specific CO₂ emission from fuel consumption.

$$EFFC_{t,coun,tech} = SNELD_{t,coun,tech} \cdot \left(\sum_{fuel} \frac{FDEM_{t,coun,fuel}}{NELDEM_{t,coun}} \cdot CC_{fuel} \right) \cdot \frac{44}{12}$$

243. $EFOP$ is the specific CO₂ emission from decarbonation. We assume that it does not depend on time or country. From [MATE, 2002] we have $EFOP = 525\text{kg CO}_2/\text{t clinker}$ for every technology.

244. So that $CVEM_{t,coun,tech}^{clink} = PC_{t,coun} \cdot (EFFC_{t,coun,tech} + EFOP - OB_{t,coun})$ where $OB_{t,coun}$ is the output-based CO₂ emission allowance of country coun at time t.

245. Finally the national CO₂ emissions from cement industry at time t are:

$$EM_{t,coun} = \sum_{tech} EM_{t,coun,tech} = \sum_{tech} PRO_{t,coun,tech} \cdot CKrate_{t,coun} \cdot (EFFC_{t,coun,tech} + EFOP)$$

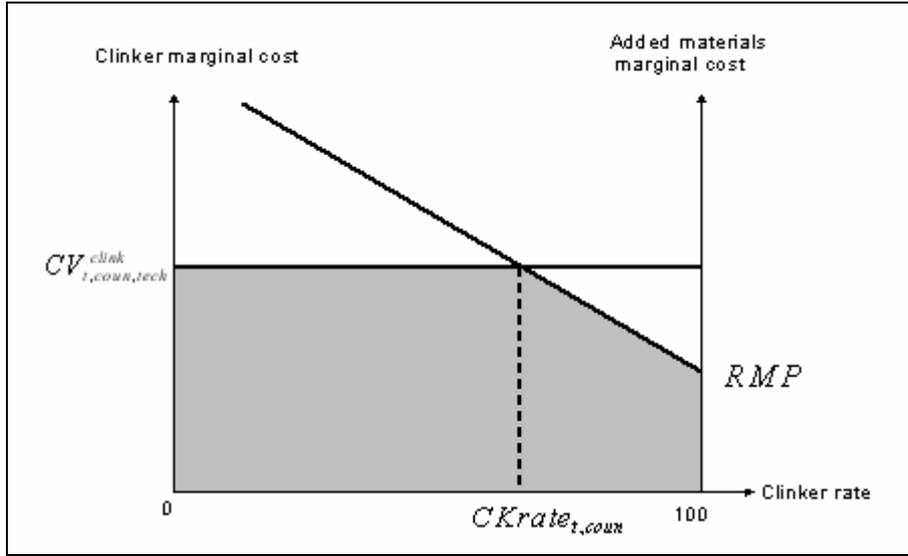
where $CKrate_{t,coun}$ is the clinker rate in country coun at time t.

Clinker rate

246. The clinker rate is a very important control lever of the cement firms on their emission. Hence, it is essential to model the clinker rate decision process. However, modelling it is very difficult. Indeed, the average clinker rate in a country is not only within the competence of the cement firms. State, through the cement standards, and before all consumers, through their preferences driven by habits, are involved in this complex process.

247. Keeping that in mind, we assume the clinker rate in a country at a given time t is an equilibrium between the variable cost of clinker and the cost of added materials. We assume the more you put added materials in cement, the more expensive it is to maintain the quality of the final cement. Therefore the marginal cost of added materials increases with quantity, whereas the clinker marginal cost is constant and equals the one we have just defined. Hence the clinker rate decision (from the firms-state-consumers trio) can be modelled as shown in the following figure:

Figure 27: Clinker rate choice



248. Because of the lack of data, we assume the marginal cost curve of added materials is linear. It depends on every country. But all the national lines go through the point: (added materials content = 0 ; RMP). It is coherent with the idea that the first gram of added materials put into the cement composition only costs its price. But the more added materials you put in cement, the more expensive it is to maintain the same final quality. The slopes of the national marginal cost lines have been calibrated so that clinker rates observed in 1997 are coherent with the decision modelling.

Variable cost of cement

249. We can finally calculate the technological variable production cost of a tonne of cement in every country by:

$$CV_{t,coun,tech} = CKrate_{t,coun} \cdot CV_{t,coun,tech}^{clink} + (1 - CKrate_{t,coun}) \cdot \left(\frac{CV_{t,coun,tech}^{clink} + RMP}{2} \right)$$

250. The grey area in the previous figure represents $CV_{t,coun,tech}$.

251. From $CV_{t,coun,tech}$ we define the average variable production cost of the country $CV_{t,coun}$, which is used by our competition model GEO in the Production and International Trade module. Since we assume

the same utilisation rate for each technology (see 0), $CV_{t,coun} = \sum_{tech} \frac{CAP_{t,coun,tech}}{CAP_{t,coun}} \cdot CV_{t,coun,tech}$ where

$CAP_{t,coun,tech}$ is the technology tech clinker capacity and $CAP_{t,coun}$ the total clinker capacity of country coun.

International competition module*World competition on the cement market*

252. Representation of international trade in CEMSIM-GEO is made through GEO. For more details on GEO, see 0.

253. GEO distinguishes two kinds of capacities: domestic capacities and export capacities. The first ones are used to satisfy domestic consumption. When not fully used, a part of these capacities can be used for export (the ones “closed” to borderline which are not using the shaft technology). The second ones are only used for export.

254. However GEO uses only one variable cost per country: the same average variable production cost is used for export and domestic productions. This unique cost is calculated as described above, mixing up domestic and export technological portfolio.

255. In GEO, a country competes on the cement market at time t through its average variable production cost, its cement domestic capacity $CAP_{t,coun}^{dom} / CKrate_{t,coun}$ and its cement export capacity $CAP_{t,coun}^{exp} / CKrate_{t,coun}$. GEO gives us for every country:

- the cement production of the country coun $PRO_{t,coun}$,
- the domestic cement price $DOMPRICE_{t,coun}$,

Remarks

256. At the beginning of the year t , a country does not know exactly its average variable production cost. Indeed, it requires the primary fuel share in primary fuel consumption which is not accessible without $PRO_{t,coun,tech}$. Variable production costs at time t are revealed at the end of time t . Consequently, countries compete through their variable costs forecast, using primary fuel shares of the previous year. This is in accordance with the real world where private companies announce at the beginning of a year the price they will practice in a given area.

Technological choice

257. The national production of a country has to be shared among technologies of its technological portfolio. We consider, and it is not the case in [Szabo *et al.*, 2003], that cement companies do not have much room for manoeuvre concerning the sharing out of their production by factory (so by technology). Indeed, transportation costs are so important that we assume a company has to produce as close as possible from the consumption area. Thus, the utilisation rate is the same for each technology:

$$PRO_{t,coun,tech} = CAP_{t,coun,tech} / CKrate_{t,coun} \cdot UR_{t,coun}$$

where $UR_{t,coun}$ is the capacity utilisation rate:

$$UR_{t,coun} = \frac{PRO_{t,coun}}{CAP_{t,coun} / CKrate_{t,coun}}$$

258. And the share of a technology in the production of a country at time t is its share in the technological portfolio of the country:

$$\frac{PRO_{t,coun,tech}}{PRO_{t,coun}} = \frac{CAP_{t,coun,tech}}{CAP_{t,coun}}$$

259. The knowledge of $PRO_{t,coun,tech}$ gives access to the exact variable production costs and so to the national profits on variable costs $PROFIT_{t,coun}$.

Technological dynamics module

260. This section comes from [Szabo *et al.*, 2003].

Retirement

261. Each technology has a defined technical lifetime $TCLT_{tech}$. We assume this lifetime is the same for every technology and equals 35 years. A factory should retire as soon as it has been used for $TCLT$ years. Such a retirement function would require the opening dates of all the cement factories in the world. To avoid this huge data work, we assume that every year, a rate $\frac{1}{TCLT}$ of each technology retires.

262. Thus, at time t , a country knows for every technology its remaining capacity at $t+1$ if no new capacities are built and no capacities are retrofitted,

$$REMCAP_{t+1,coun,tech} = CAP_{t,coun,tech} \cdot \left(1 - \frac{1}{TCLT}\right),$$

and its total remaining capacity

$$REMCAP_{t+1,coun} = CAP_{t,coun} \cdot \left(1 - \frac{1}{TCLT}\right).$$

Retrofitting

263. Remaining capacities can be reallocated among technologies by means of a generalized retrofitting procedure. According to this procedure, a share $RFTSH_{tech}$ of the remaining capacity of technology $tech$, $REMCAP_{t+1,coun,tech}$, is available for retrofitting options.

264. A share $RFTFRA_{t+1,coun,tech \rightarrow i}$ of these “available” capacities of technology $tech$ is transformed into technology i , depending on the retrofitting costs and the allowed possibilities for technology upgrade.

265. $RFTCAP_{t+1,coun,i}$ is the aggregation of the capacity flows from any technology to technology i :

$$RFTCAP_{t+1,coun,i} = \sum_{tech} CAPFLW_{t+1,coun,tech \rightarrow i}$$

where $CAPFLW_{t+1,coun,tech \rightarrow i} = RFTSH_{tech} \cdot REMCAP_{t+1,coun,tech} \cdot RFTFRA_{t+1,tech \rightarrow i}$.

266. Finally, if we name $CAP_{t+1,coun,tech}^{w/o}$ the total clinker capacity of technology tech at t+1 (after retrofitting process between t and t+1) if no new capacities are built, we have:

$$CAP_{t+1,coun,tech}^{w/o} = REMCAP_{t+1,coun,tech} \cdot (1 - RFTSH_{t+1,coun,tech}) + RFTCAP_{t+1,coun,tech}$$

Remarks. $CAP_{t+1,coun}^{w/o} = \sum_{tech} CAP_{t+1,coun,tech}^{w/o} = REMCAP_{t+1,coun}$

267. A crucial parameter in the retrofitting process is $RFTFRA_{t+1,coun,tech \rightarrow i}$, i.e. the retrofitted fraction from technology tech to technology i between t and t+1. $RFTFRA_{t+1,coun,tech \rightarrow \cdot}$ is a vector whose components are numbers between 0 and 1, and summing 1. We now explain how it is calculated.

268. $AUXRFTFRA_{t+1,coun,tech \rightarrow \cdot}$ is the theoretical vector. $AUXRFTFRA_{t+1,coun,tech \rightarrow i}$ is a function of the retrofitting costs at this time ($RFTCST_{t+1,coun,tech \rightarrow i}$), of the forecast clinker variable costs of technologies tech and i at t+1 ($CV_{t+1,coun,tech}^{clink,ante}$ and $CV_{t+1,coun,i}^{clink,ante}$) and some auxiliary variables :

$$RFTCST_{t+1,coun,tech \rightarrow i} = RFTCST_{t,coun,tech \rightarrow i} \cdot \left(\frac{IC_{t,i}}{IC_{t-1,i}} \right)$$

$$RFTCST_{0,coun,\cdot \rightarrow \cdot} = RFTMTX_{coun}$$

$$AUXRFTFRA_{t+1,coun,tech \rightarrow i} = \frac{e^{\left(\beta_{tech,i} \cdot \left(RFTCST_{t+1,coun,tech \rightarrow i} \cdot \left(\frac{DR \cdot (1+DR)^{ELT}}{(1+DR)^{ELT} - 1} \right) + CV_{t+1,coun,i}^{clink,ante} - CV_{t+1,coun,tech}^{clink,ante} \right) \right)}}{\sum_i e^{\left(\beta_{tech,i} \cdot \left(RFTCST_{t+1,coun,tech \rightarrow i} \cdot \left(\frac{DR \cdot (1+DR)^{ELT}}{(1+DR)^{ELT} - 1} \right) + CV_{t+1,coun,i}^{clink,ante} - CV_{t+1,coun,tech}^{clink,ante} \right) \right)}}$$

269. The variable costs by technology at t+1 are forecast by firms like in the following section. $IC_{t,i}$ is the investment cost at time t for a one-tonne clinker factory of technology i (see below).

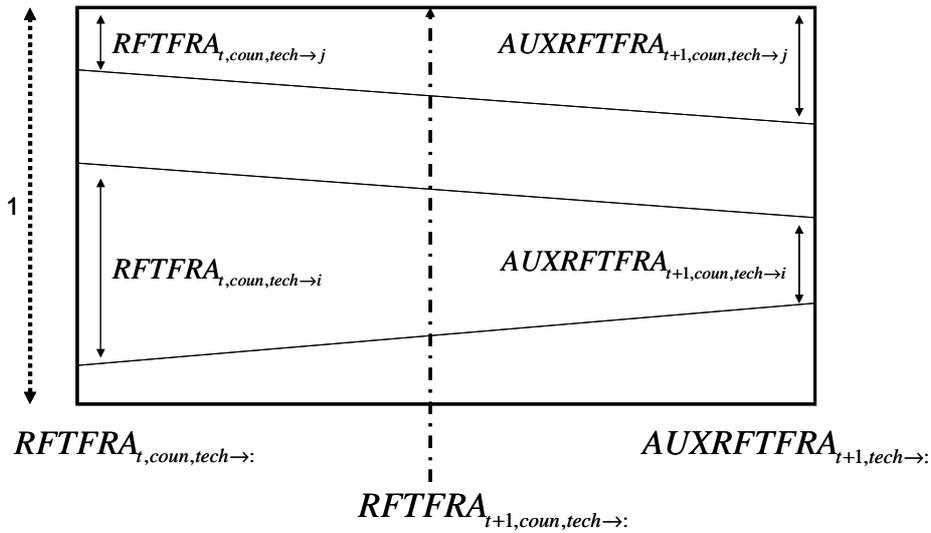
270. $RFTMTX_{coun}$ is the retrofitting cost matrix of country coun. We give as an example the matrix of Austria in €99:

Tableau 9: Retrofitting cost matrix

From / To	SWET	DRYL	SHAFT	SDRY	DRYPH	WETL	DRYPC
SWET	0	12500	12500	37,5	93,75	12500	137,5
DRYL	12500	0	12500	12500	62,5	12500	93,75
SHAFT	12500	12500	0	12500	12500	12500	12500
SDRY	12500	12500	12500	0	62,5	12500	93,75
DRYPH	12500	12500	12500	12500	0	12500	35
WETL	12,5	12500	12500	37,5	93,75	0	137,5
DRYPC	12500	12500	12500	12500	12500	12500	0

271. If the norm of the difference between the last value of the retrofitted fraction $RFTFRA_{t,coun,tech \rightarrow :}$ and the theoretical one $AUXRFTFRA_{t+1,tech \rightarrow :}$ is greater than a certain limit D, the current vector $RFTFRA_{t+1,coun,tech \rightarrow :}$ is set as an intermediate value between them. Otherwise, the current vector is set to the value of the theoretical one. D has been calibrated by IPTS team to get the best fit to real retrofitting speed.

Figure 28: Retrofitting fraction



$$RFTFRA_{t+1,coun,tech \rightarrow :} = \begin{cases} \text{If} & \sqrt{\sum_{tech_j} \left(RFTFRA_{t,coun,tech \rightarrow tech_j} - AUXRFTFRA_{t+1,coun,tech \rightarrow tech_j} \right)^2} > D \\ \text{Then} & \theta_{t+1,coun,tech} \cdot AUXRFTFRA_{t+1,coun,tech \rightarrow :} + (1 - \theta_{t+1,coun,tech}) \cdot RFTFRA_{t,coun,tech \rightarrow :} \\ \text{Else} & AUXRFTFRA_{t+1,coun,tech \rightarrow :} \end{cases}$$

The intermediate value $\theta_{t+1,coun,tech}$ is the value that makes

$$\sqrt{\sum_{tech_j} \left(RFTFRA_{t+1,coun,tech \rightarrow tech_j} - AUXRFTFRA_{t+1,coun,tech \rightarrow tech_j} \right)^2} = D$$

Substituting for $RFTFRA_{t+1,coun,tech \rightarrow :}$ in the previous equation, $\theta_{t+1,coun,tech}$ is found as:

$$\theta_{t+1,tech} = \begin{cases} \text{If} & \sqrt{\sum_{tech_j} \left(RFTFRA_{t,coun,tech \rightarrow tech_j} - AUXRFTFRA_{t+1,coun,tech \rightarrow tech_j} \right)^2} > D \\ \text{Then} & \sqrt{\frac{D^2}{A_{tech} + B_{tech} - 2 \cdot C_{tech}}} \\ \text{Else} & 1 \end{cases}$$

where:

$$A_{tech} = \sum_{tech_j} RFTFRA_{t,coun,tech \rightarrow tech_j}^2$$

$$B_{tech} = \sum_{tech_j} AUXRFTFRA_{t+1,coun,tech \rightarrow tech_j}^2$$

$$C_{tech} = \sum_{tech_j} \left(RFTFRA_{t,coun,tech \rightarrow tech_j} \cdot AUXRFTFRA_{t+1,coun,tech \rightarrow tech_j} \right)$$

Investment decision module

Amount of new capacities built

272. In CEMSIM-GEO, the behaviour of investors concerning the amount of new capacities built is modelled through GEO capacity planning, GEOcp, a modified version of GEO. For more details, see Annex II.

273. At time t, every country foresees its consumption, its production costs and its production capacity at time t+1+Y. These forecasts are assumed to be shared among all the producers of the world. They are the inputs of GEOcp. GEOcp determines the equilibrium resulting from these inputs.

274. Let us say we are at the end of period t. Every country has to:

- forecast its consumption at time t+1+Y, $CON_{t+1+Y,coun}^{ante}$;
- forecast the variable production cost of its remaining capacities, $RCV_{t+1+Y,coun}^{ante}$, and to forecast the variable cost of the new capacity it can build, $NCV_{t+1+Y,coun}^{ante}$;
- forecast the retirement of its capacities “between t and t+1+Y” and so its remaining domestic and export clinker capacities, $REMCAP_{t+1+Y,coun}^{dom}$ and $REMCAP_{t+1+Y,coun}^{exp}$.

Assessment of the expected consumption $CON_{t+1+Y,coun}^{ante}$

275. We assume population and GDPPOP at time t+1+Y are perfectly forecast by producing countries. They forecast the national consumptions using the consumption formula and the domestic price forecast at time t+1+Y-1:

$$DOMPRICE_{t+1+Y-1,coun}^{ante} = \frac{Y}{5} \cdot \left(\sum_{u=t-4}^t \frac{DOMPRICE_{u,coun}}{DOMPRICE_{u-1,coun}} \right) \cdot DOMPRICE_{t,coun}$$

So that

$$CON_{t+1+Y,coun}^{ante} = CON_{t+1,coun} \cdot \left(\frac{PGCON_{t+1+Y,coun}}{PGCON_{t+1,coun}} \right) \cdot \left(\frac{GDPPPOP_{t+1+Y,coun}}{GDPPPOP_{t+1,coun}} \right) \cdot \left(\frac{POP_{t+1+Y,coun}}{POP_{t+1,coun}} \right) \cdot \left(\frac{DOMPRICE_{t+1+Y-1,coun}}{DOMPRICE_{t,coun}} \right)^{PRE_{coun}}$$

Assessment of the remaining capacities

276. Countries have access to their clinker production capacities at time $t+1+Y$ if no new capacities are built, using the simplified expressions:

$$REMCAP_{t+1+Y,coun}^{dom} = REMCAP_{t+1,coun}^{dom} \cdot \left(1 - \frac{1}{TCLT} \right)^Y$$

$$REMCAP_{t+1+Y,coun}^{exp} = REMCAP_{t+1,coun}^{exp} \cdot \left(1 - \frac{1}{TCLT} \right)^Y$$

Assessment of the variable production cost of remaining capacities $RCV_{t+1+Y,coun}^{ante}$

277. We assume that a country is able to perfectly anticipate at time t the value at $t+1+Y$ of fuels and electricity prices. It is able to anticipate the CO_2 price and the output-based CO_2 allowance at time $t+1$. For the other parameters, a country uses time t values to make its anticipation.

278. A country uses this variable cost to forecast the clinker rate it will apply at time $t+1+Y$ (see above).

Assessment of the variable production cost of new capacities $NCV_{t+1+Y,coun}^{ante}$

279. We assume the variable production cost of a tonne of clinker with a new capacity using technology $tech$ is the sum of the technological variable cost of remaining capacities and of the fixed costs that have to be paid at time $t+1$.

280. The fixed costs of the different technologies at time $t+1$ are the sum of the fixed operation costs and maintenance costs, $CFOM_{t+1,coun,tech}$ (€/tonne of capacity), and the investment costs, $IC_{t+1,coun,tech}$ (€/tonne of capacity), discounted through the economic lifetime of the technology, ELT ³⁹ (year), to the rate DR :

$$CF_{t+1,coun,tech} = CFOM_{t+1,coun,tech} + IC_{t+1,coun,tech} \cdot \frac{DR \cdot (1+DR)^{ELT}}{(1+DR)^{ELT} - 1} \text{ (€/tonne of capacity)}$$

281. The fixed operation costs and maintenance costs are assumed to be 5% of the investment costs.

³⁹ In our model, the economical lifetime is the same for any technology, and equals the technical lifetime, 35 years.

282. The investment costs of the technologies are represented by a learning curve depending on the previous value of the investment cost, the cumulate capacity $CUMCAP_{t,coun,tech}$ (i.e. the total capacity of technology tech that has been built until t in tonne of capacity, taking into account retrofitting) and the elasticity $CE_{coun,tech}$.

$$IC_{t+1,coun,tech} =$$

$$\text{If } CUMCAP_{t,coun,tech} > 0$$

$$\text{Then } IC_{t,coun,tech} \cdot \left(\frac{CUMCAP_{t,coun,tech}}{CUMCAP_{t-1,coun,tech}} \right)^{CE_{coun,tech}}$$

$$\text{Else } IC_{t,coun,tech}$$

$$\text{with } CUMCAP_{t,coun,tech} = CAP_{0,coun,tech} + \int_0^t (NWBCAP_{\tau,coun,tech} + RFTCAP_{\tau,coun,tech}) d\tau.$$

$$\text{So that } NCV_{t+1+Y,coun}^{ante} = \sum_{tech} TSHNW_{t+1,coun,tech} \cdot (CF_{t+1,coun,tech}^{ante} + RCV_{t+1+Y,coun,tech}^{ante}).$$

where $TSHNW_{t+1,coun,tech}$ is the technological share of technology tech in the new built capacities, defined in next subsection.

283. All these forecasts are assumed to be shared among all the producers of the world. They are the inputs of GEOcp. GEOcp determines the amount of new capacities every country builds. Then, the countries have to decide what technologies they use.

Technological choice for new capacities

284. We assume:

$$NWBCAP_{t+1,coun,tech}^{dom} = NWBCAP_{t+1,coun}^{dom} \cdot \frac{\frac{CAP_{t,coun,tech}}{CAP_{t,coun}} (RCV_{t+1,coun,tech}^{ante} + CF_{t+1,coun,tech}^{ante})^{-SPP}}{\sum_{tech_i} \frac{CAP_{t,coun,tech_i}}{CAP_{t,coun}} (RCV_{t+1,coun,tech_i}^{ante} + CF_{t+1,coun,tech_i}^{ante})^{-SPP}}$$

$$NWBCAP_{t+1,coun,tech}^{exp} = NWBCAP_{t+1,coun}^{exp} \cdot \frac{\frac{CAP_{t,coun,tech}}{CAP_{t,coun}} (RCV_{t+1,coun,tech}^{ante} + CF_{t+1,coun,tech}^{ante} + A_{tech})^{-SPP}}{\sum_{tech_i} \frac{CAP_{t,coun,tech_i}}{CAP_{t,coun}} (RCV_{t+1,coun,tech_i}^{ante} + CF_{t+1,coun,tech_i}^{ante} + A_{tech})^{-SPP}}$$

where A=1000 for the shaft technology and 0 for others. It traduces the fact that the shaft technology is excluded from international trade, considering that quality of clinker with this technology is not sufficient.

285. The second expression of the right member of the first equation is $TSHNW_{t+1,coun,tech}^{dom}$, the technological share of technology tech in the new built domestic capacities. The second expression of the right member of the second equation is $TSHNW_{t+1,coun,tech}^{exp}$, the technological share of technology tech in

the new built export capacities. As a simplification, the technological share $TSHNW_{t+1,coun,tech}$ used in the definition of $NCV_{t+1+Y,coun}^{ante}$ is $TSHNW_{t+1,coun,tech}^{dom}$.

286. SPP is a substitution parameter depending only on the country. With positive SPP value, a technology share decrease when its production cost grows. High SPP value allows faster shifting to cheaper technologies. If SPP tends to zero, the technologies are distributed evenly.

Annex IV:
TECHNOLOGICAL EVOLUTIONS IN THE CEMENT INDUSTRY

BaU scenario

Variable production cost

287. As explained in the main text, we distinguish two production costs: the variable production cost (including energy cost, raw material cost and variable operation and maintenance cost) and the fixed production cost (investment cost and fixed operation and maintenance cost). We consider, through GEO, that the determining factor of the international competition, when production capacities are fixed, is the variable production cost. That's why we focus on it and on its evolution through time in this section.

288. The national variable production costs are driven by energy costs⁴⁰: electric energy and non-electric energy (energy from fuel combustion). It is worth noting that at the world level energy cost account for more than half of the total variable production cost of a tonne of cement, fuel energy cost for 65% of the energy cost and electric energy cost for 35% of the energy cost.

Fuel energy cost

289. Fuel energy cost is driven by fuel prices⁴¹ and fuel shares on the one hand and on the other hand by energy efficiency improvements:

- yearly improvements of the new available machines⁴², which we assume exogenous from the cement manufacturers point of view,
- improvements due to the cement manufacturers themselves (endogenous improvements), concerning either the reduction of the clinker rate in cement - clinker is the intensive energy and carbon intermediary product in the cement manufacturing process - either the switch from low to high efficient technologies through the retrofitting of existing capacities or the building of new energy efficient plants. Foreseeing energy and money savings, the investors progressively retrofit the capacities using low efficient technologies toward efficient ones. For the same reason, the new built capacities tend to use more energy efficient technologies.

Fuel prices, fuel shares

290. Fuel shares are driven by the fuel utilisation costs⁴³, derived from POLES, and highly depend on the inertia of the fuel combustion system in the cement industry. For an illustrative purpose, we present in

⁴⁰ Variable operation and maintenance costs and the raw material cost are assumed to be constant through time.

⁴¹ Primary fuel prices are exogenous inputs from POLES. Coke and WWF prices are calibrated on the primary fuel prices (see Annex III).

⁴² We assume the energetic performance of the new machines increases by 0.5% every year.

the two following figures the estimated evolution of fuel costs in the Canada and the evolution of fuel shares in the fuel consumption of the Canadian cement industry.

Figure 29: BaU / Fuel costs in Canada

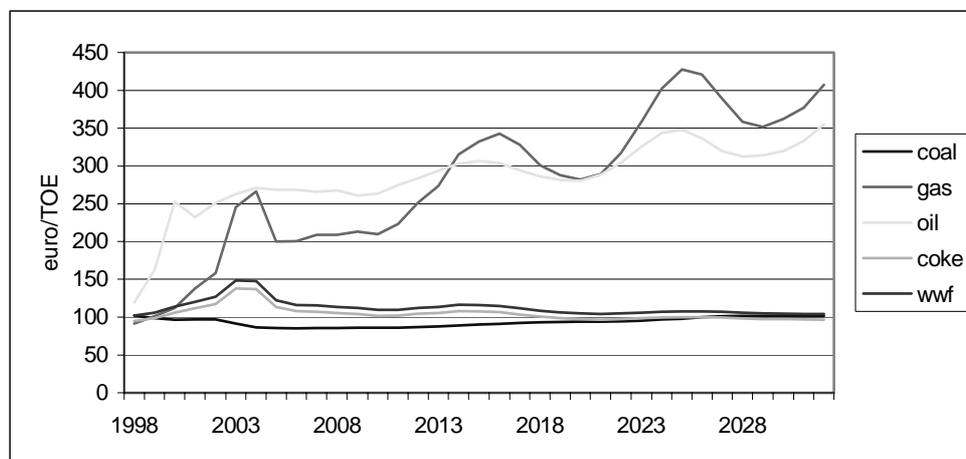
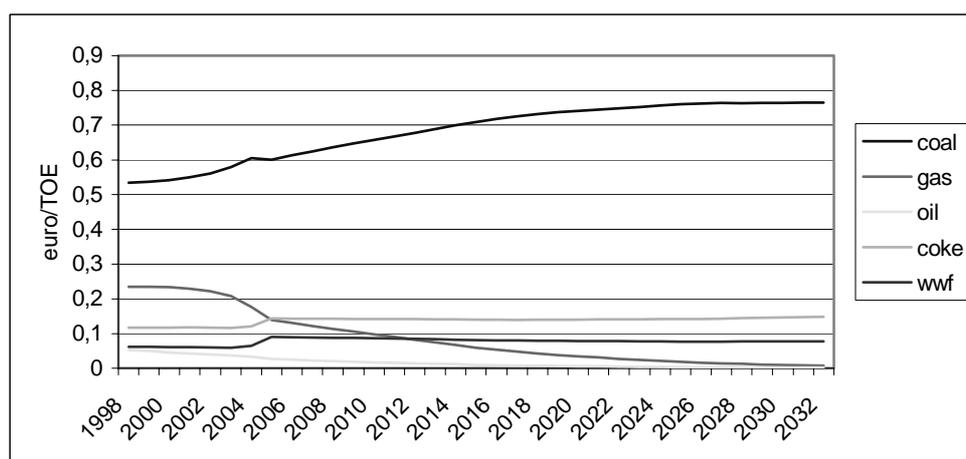


Figure 30: BaU / Fuel shares in Canada



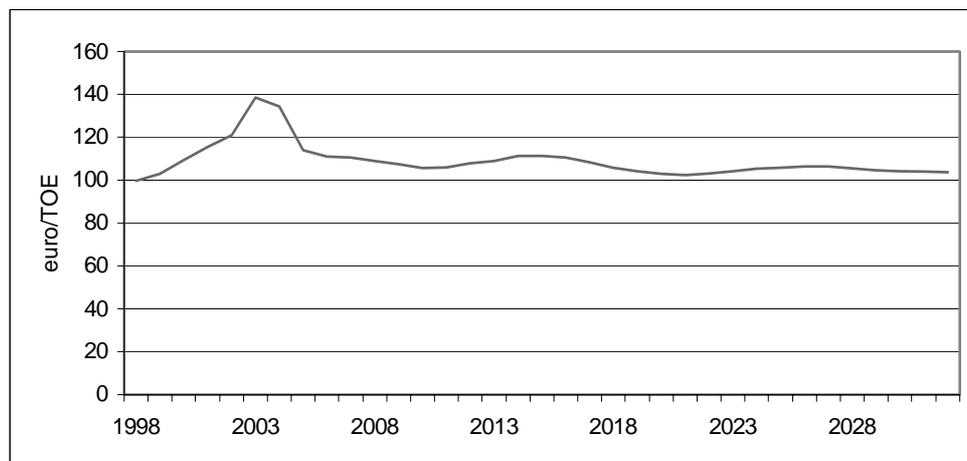
291. We observe that the increase in the utilisation costs of oil and gas leads Canadian cement manufacturers to switch progressively from these fuels to coal. Whereas coke and WWF are almost as cheap as coal, their shares do not increase. Indeed, because of the inertia of the combustion system, emerging fuels need to be very competitive to increase significantly their shares, especially in countries where the cement business is decreasing.

292. The fuel prices and the fuel shares in a country determine its average fuel cost. In Canada, the average fuel cost evolves as shown below:

⁴³

The utilisation cost of a given fuel equals its price (€/TOE) + its emission cost (€/TOE) divided by its efficiency rate. The emission cost of a fuel is its CO₂ content (t CO₂ /TOE) multiplied by the CO₂ price (€/t CO₂).

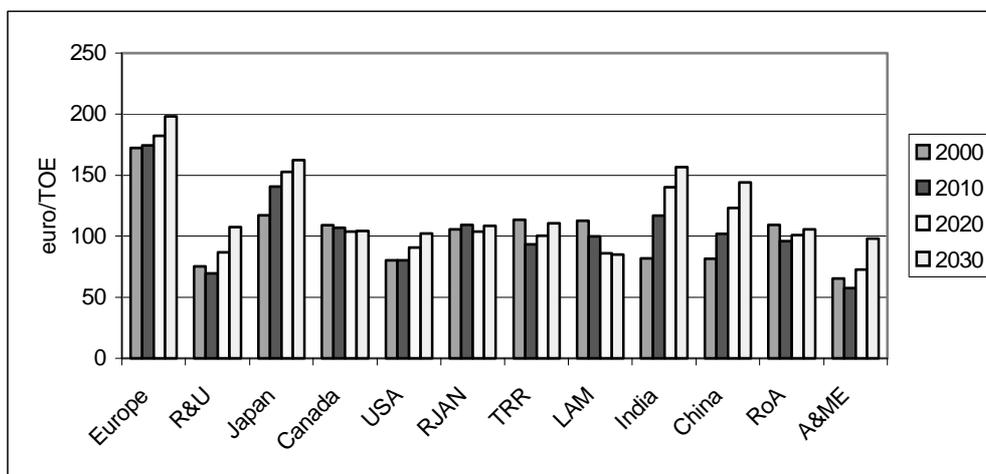
Figure 31: BaU / Average fuel cost in Canada



293. We observe that, in spite of the consequent increase of the oil and gas costs, Canadian manufacturers succeed in maintaining their average fuel cost around 110 euro / TOE, thanks to the switch to coal.

294. The evolutions of the average fuel costs by region are given in the following figure:

Figure 32: BaU / Average fuel cost

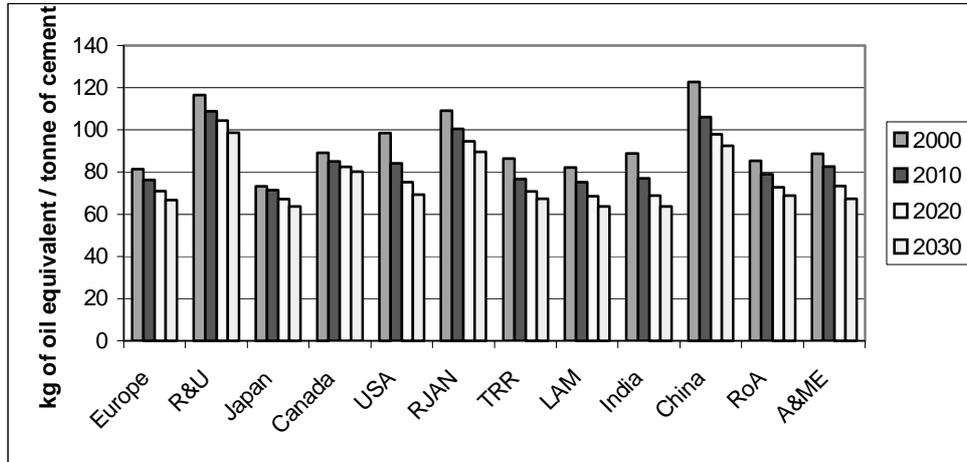


295. At the world level, the average fuel cost increases by 25% between 2000 and 2030, from 100 to around 125 euro/TOE.

Fuel energy efficiency improvements

296. In the following figure, we represent the evolution of the fuel energy consumption per tonne of cement by region:

Figure 33: BaU / Fuel consumption per tonne of cement

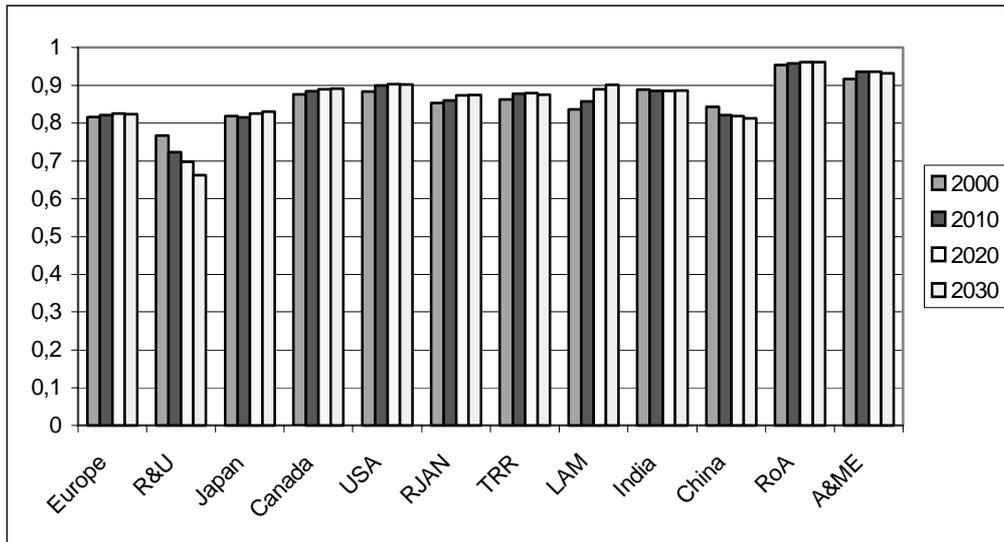


297. We observe a significant drop in the fuel energy consumption per tonne of cement throughout the world. At the world level, it decreases by 25% between 2000 and 2030, from 100 to 75 kg of oil equivalent per tonne of cement.

Clinker rate

298. Most of the fuel energy efficiency improvements are not due to the decrease in the national clinker rates. Indeed, except in R&U and in LAM, the clinker rates remain more or less constant, as we can see in the following figure. By construction, the national clinker rate decreases in the countries where the production cost of clinker increases, and conversely.

Figure 34: BaU / Clinker rate

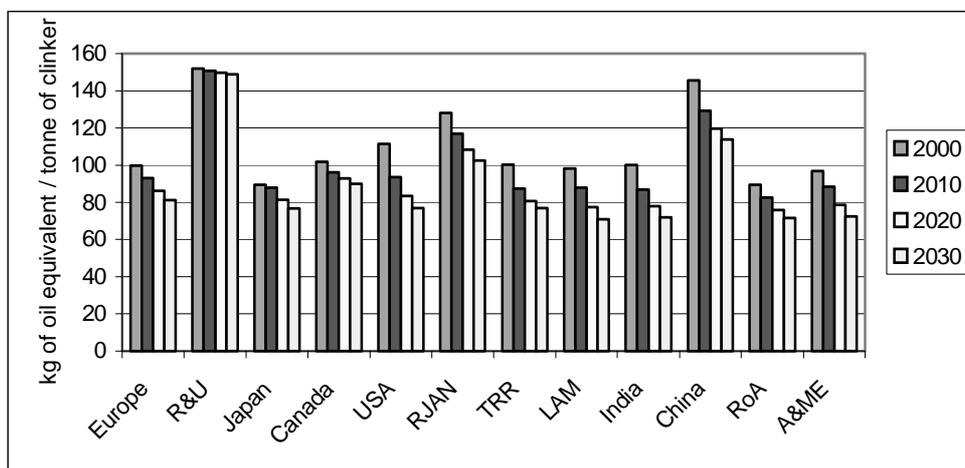


299. At the world level, the average clinker rate remains almost constant: 0.86% in 2000, 0.88 in 2030.

Fuel consumption per tonne of clinker

300. In the following figure, we observe an important decrease in the fuel consumption per tonne of clinker in every region.

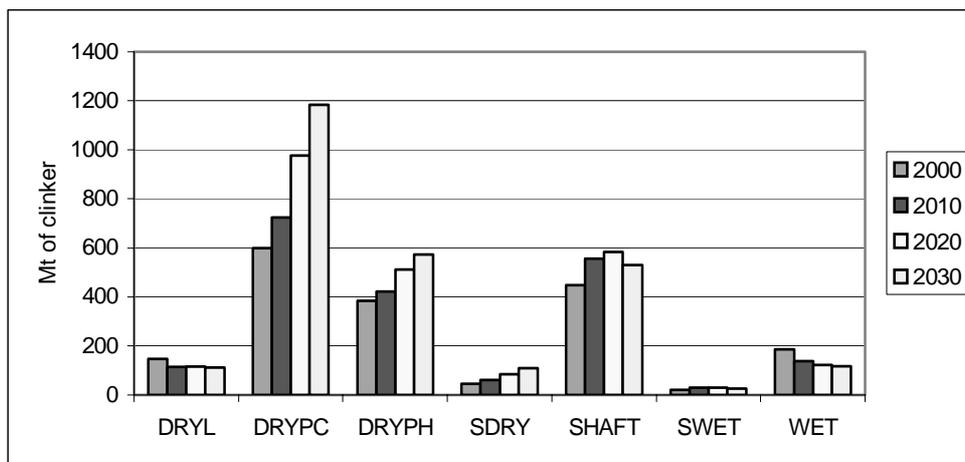
Figure 35: BaU / Fuel consumption per tonne of clinker



301. At the world level, it decreases from 116 in 2000 to 86 kg of oil equivalent per tonne of clinker in 2030. These improvements are on the one hand exogenous, and on the other hand endogenous. At the world level, the exogenous improvements represent around 80% of the total energy improvements: without retrofitting and if the companies would make through time the same technological choices than in 2000 for the building of new capacities, the average fuel consumption per tonne of clinker in the world would reach around 90 kg in 2030.

302. The other energy efficiency improvements are endogenous improvements - the ones linked to energy-efficient technological choices made by manufacturers in retrofitting and new capacities building. We observe for instance that the dry precalciner technology (DRYPC), the most energy efficient one, increases its share in the world capacity from 33% in 2000 to 45% in 2030.

Figure 36: BaU / Capacity by technology

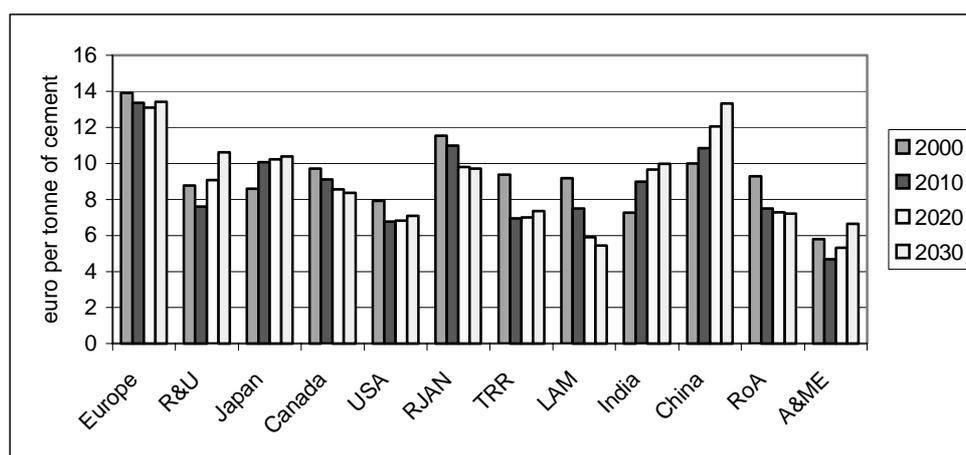


303. On figure X, we notice that Russia and the Ukraine do not improve significantly their fuel energy efficiency. These countries having a huge excess of capacity, they do not build new efficient plants. Energy efficiency improvements only come from retrofitting. On the opposite, consequent energy improvements occur in the countries where many capacities (related to their total capacity) are built, like the USA and China between 2000 and 2010. These examples highlight the importance of new capacities in energy efficiency improvements.

304. We also notice that the fuel efficiency in some countries remains much lower than in others. In the Chinese case, this is mostly due to the inertia of the system. More than 80% of the Chinese capacities use the shaft technology in 2000. Because of inertia, Chinese producers keep on building plants using this energy-inefficient technology. Its share in new plants decreases slowly through time (77% in 2000, 70 in 2010, 66 in 2020 and 63 in 2030) but remains important because of the initial conditions. In other cases, RJAN for example, this is mostly due to the fact that the high energy costs of low efficient technologies are offset by their low investment costs.

305. These worldwide energy efficiency improvements partially offset the almost worldwide increase in average fuel costs. Finally, fuel production costs per tonne of cement evolve as shown in the following figure.

Figure 37: BaU / Fuel production cost

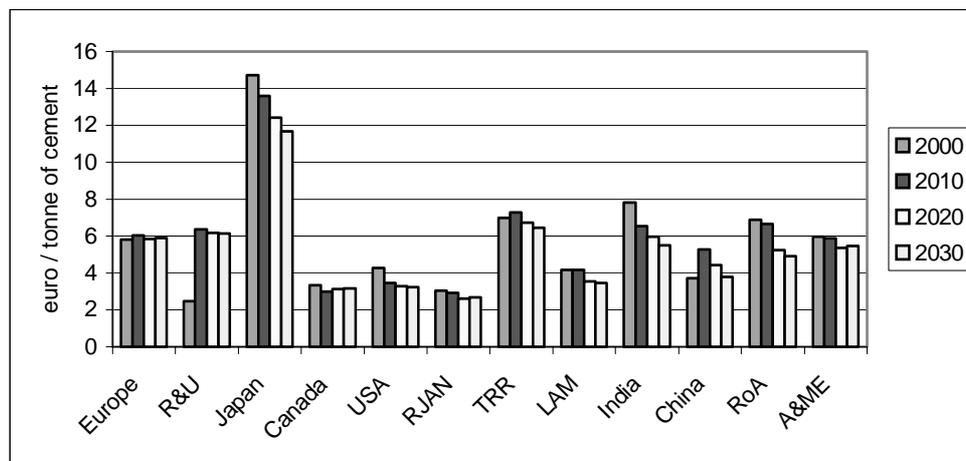


306. At the world level, the average fuel production cost remains constant around 9.5€ per tonne of cement.

Electric energy cost

307. Electric energy costs are driven by electric prices, exogenous input from POLES, and by the electric energy efficiency improvements. Electric efficiency improves mostly with the building of new capacities which are more and more energy efficient through time, but also with the retrofitting of old capacities and the resort to more efficient technologies. At the world level, the average electric consumption decreases from 10 kg of oil equivalent per tonne of clinker in 2000 to 8 in 2030 and from 9 kg of oil equivalent per tonne of cement in 2000 to 7 in 2030. The average electric production cost decreases from 5.5€ per tonne of cement in 2000 to 5 in 2030. Electric production costs per tonne of cement by regions evolve as shown in the following figure.

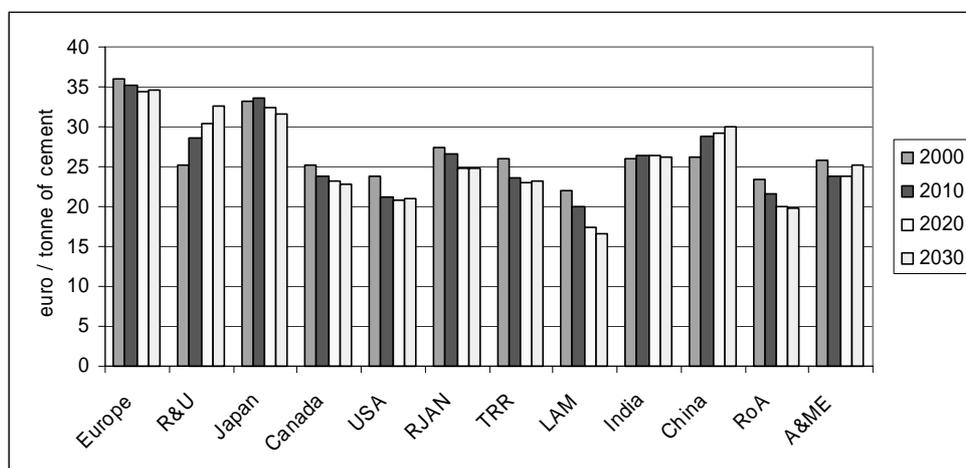
Figure 38: BaU / Electric production cost



308. We notice that the share of electric costs in total energy costs highly depend on the country considered. In Japan for example, electric costs account for more than 60% of the total energy costs in 2000, because of the particularly high electric prices. We also notice the consequent rise in the electricity prices in R&U leading to a high increase in their electric energy production costs.

309. Finally, the total variable production cost at the world level slightly decreases from 27€ per tonne of cement in 2000 to 25.5€ in 2030. At the regional level, the total variable production costs evolve as shown in the following figure.

Figure 39: BaU / Variable production cost



CO₂ emissions

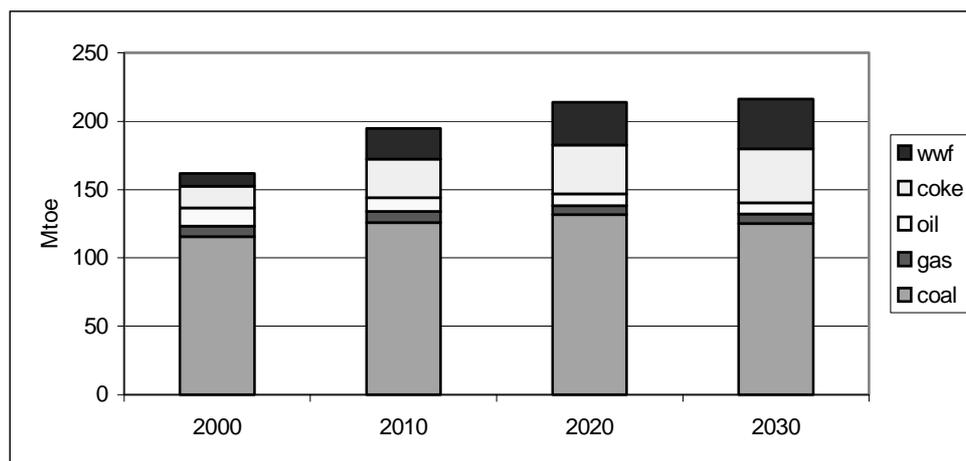
310. At the world level, we notice that, between 2000 and 2030, the emission growth is lower than the consumption growth. This is due to the evolution of the world specific emissions which decrease from 810 in 2000 to 700 kg of CO₂ per tonne of cement in 2030 (-14%). This decrease is due:

311. On the one hand, to a drop in the fuel consumption per unit of cement produced. This drop does not come from the decrease of the clinker content (see above). It comes mostly from exogenous

improvements, but also from the use of more energy efficient technologies, as we have just seen previously.

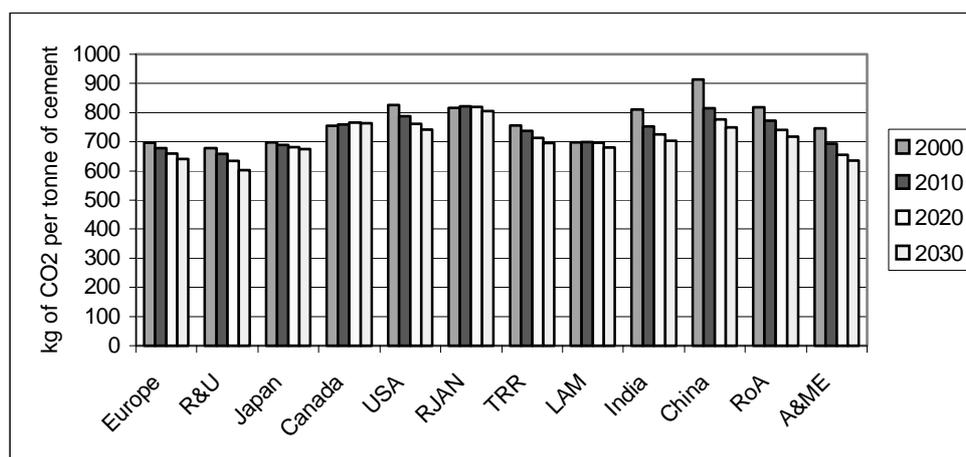
312. On the other hand, this decrease is due to the use of less carbon intensive fuels, like the Waste and Wood Fuels (WWF) which cause, according to our assumption, no CO₂ emissions. The world specific emissions per toe of fuel decrease from 3.6 to 3.2t CO₂/toe between 2000 and 2030 (-11%). This switch is only a question of relative prices.

Figure 40: BaU / World energy consumption



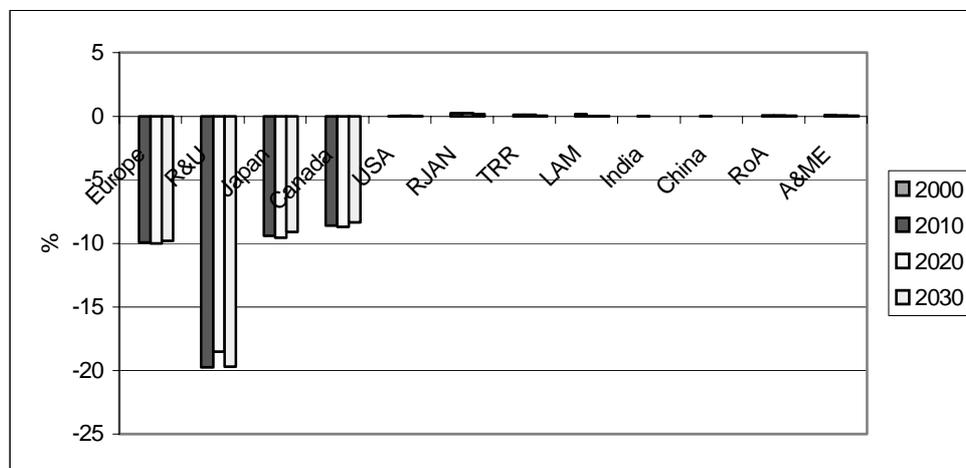
313. At the regional level, we observe the same drop in the emissions per tonne of cement, except in Canada. Indeed, the average emission per toe of fuel in Canada increases from 3.3 to 3.7t CO₂/toe between 2000 and 2030, because of the relative fuel prices that lead the manufacturers to rise their consumption of coal. Until 2020, this increase is not offset by sufficient fuel energy efficiency improvements.

Figure 41: BaU / CO₂ emissions per tonne of cement



No BTA

314. The introduction of a CO₂ price leads the cement manufacturers to decrease their emissions per tonne of cement. We can distinguish three way of reducing the specific emissions: reduction of the clinker rate, improvement of the energy efficiency and use of low carbon fuels.

Reduction of the clinker rate**Figure 42: No BTA / Clinker rates compared to BaU**

315. We observe in the annex B countries a decrease in the clinker rates. Cement manufacturers react to the increase in their clinker production cost by using less clinker and more added materials. The intensity of the drop in the clinker rate depends on country. In the countries where the cost of the added materials does not increase consequently with the increase of their use, the cement manufacturers can reduce massively the clinker rate. It is the case in R&U (around -18%). On the contrary, the reduction in the clinker rate in Canada is weak (around -8%).

316. In average, the clinker rate in Annex B countries decrease by 11% to reach 72% in 2010, 2020 and 2030 (81% in BaU).

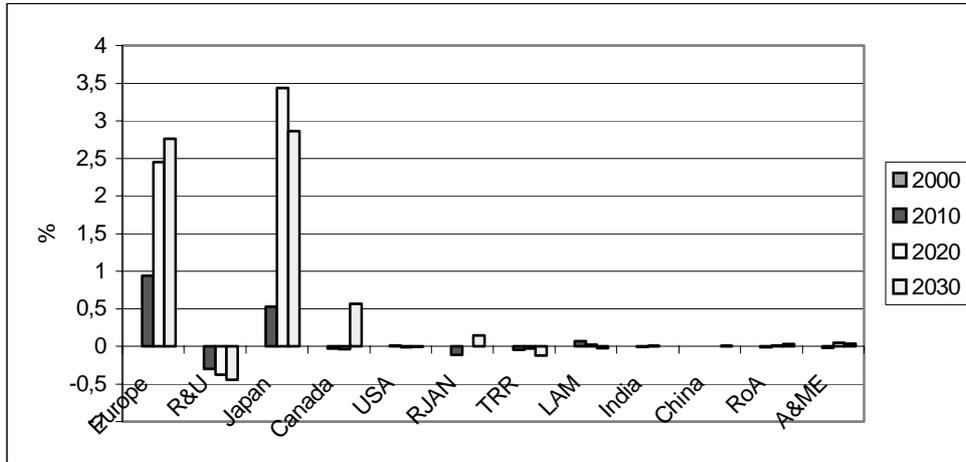
Improvement of energy efficiency

317. It is intuitive that, with the implementation of the climate policy, the cement manufacturers of the Annex B countries will improve their fuel energy efficiency compared to BaU by retrofitting their energy intensive plant into more efficient ones and by using the most efficient technologies in their new plants. It is what they actually do. However, the positive effect of these actions is limited: except in R&U, the Annex B countries already use efficient plants and build their new plants using the most efficient technologies.

318. Moreover, this positive effect is offset by the fact that the climate policy leads the countries to build much less new plants that they were supposed to build in BaU, their production decreasing. So, the cement manufacturers of the Annex B do not benefit from the exogenous energy improvements of the machines, *i.e.* from the fact that for example a plant built in 2020 is more energy efficient than a plant built in 2000 with the same technology (it consumes around 20% less energy). This negative effect has no impact on Canada before 2030 and on R&U which do not build new capacities in BaU.

319. Therefore, except in R&U (positive effect not limited and no negative effect) and in Canada before 2030 (positive effect limited but no negative effect), the climate policy has a negative impact on the energy efficiency of cement manufacturers:

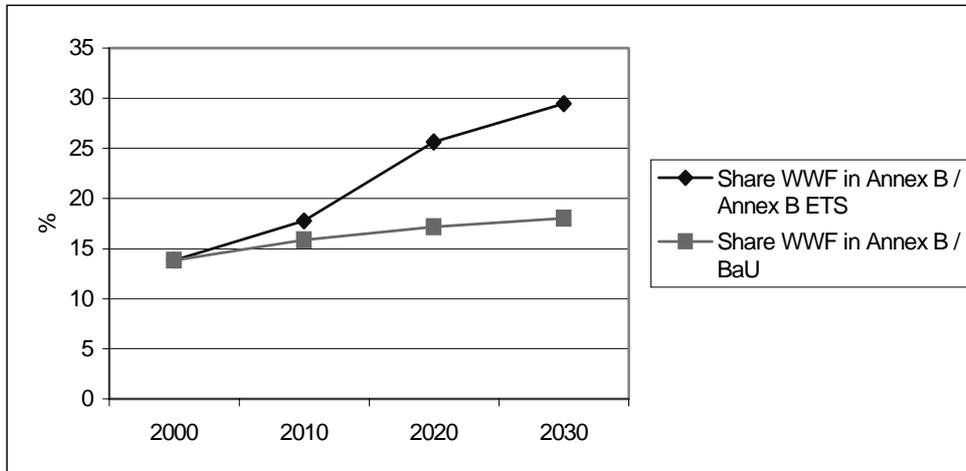
Figure 43: No BTA / Fuel consumption per tonne of clinker compared to BaU



Use of low carbon fuels

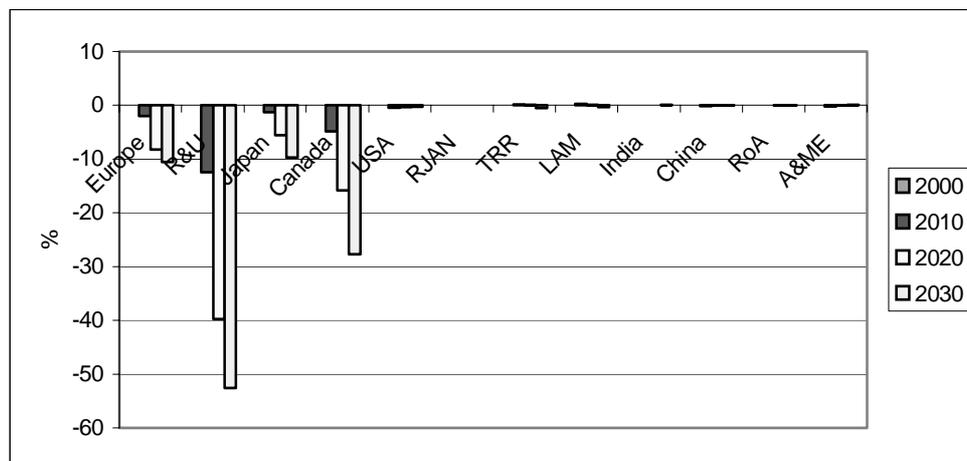
320. The CO₂ price induces shifts in fuel consumption, from C-intensive to low-C fuels. In Annex B countries, the share of WWF (which involves no CO₂ emissions under our assumptions) consequently increases compared to BaU:

Figure 44: Share of waste and wood fuels under BaU and No BTA



321. Thus, in the Annex B countries, the CO₂ emissions per toe of fuel used decrease. This drop at the regional level highly depends on the fuel relative prices.

Figure 45: No BTA / CO₂ emission per TOE of fuel compared to BaU



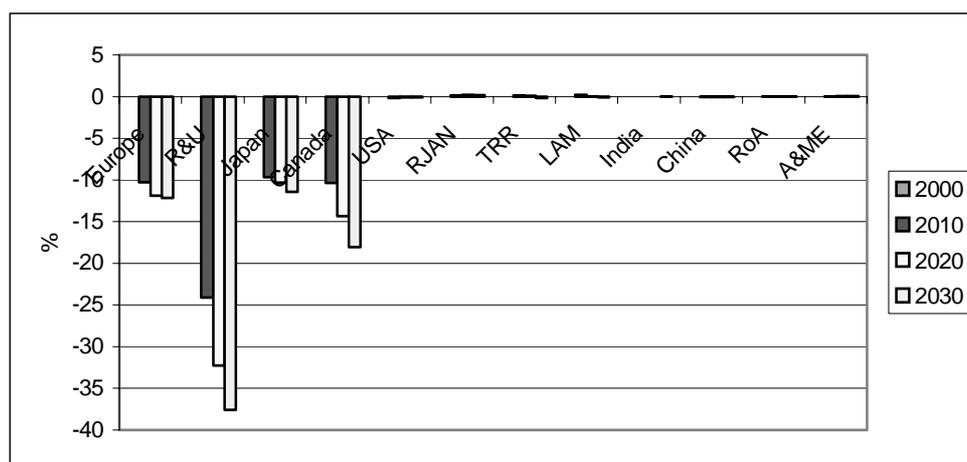
322. In average, emission per TOE of fuel in Annex B decreases by 3% in 2010 (11% in 2020, in 15% 2030).

323. Finally, the CO₂ price leads the cement manufacturers to decrease their emissions per tonne of cement by reducing the content of clinker in cement (-11% in 2030) and by reducing the emissions per TOE of fuel used (-25% in 2030). We notice that their energy efficiency slightly decreases.

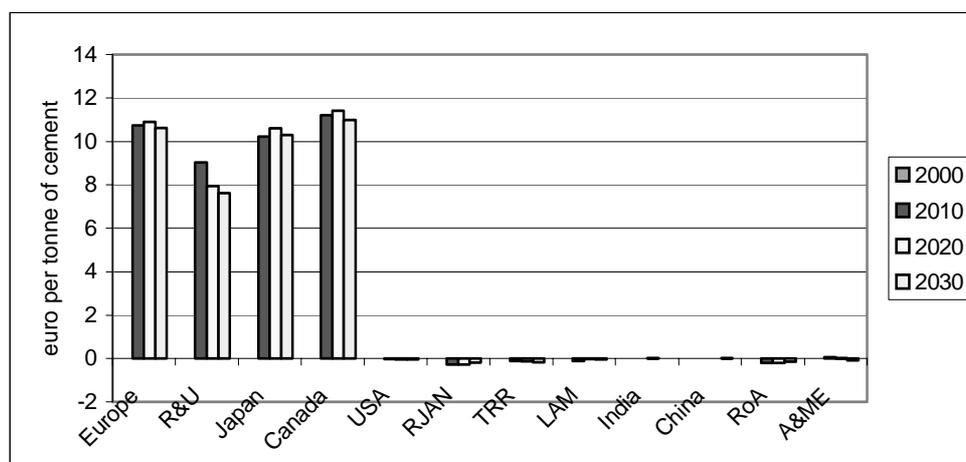
324. The slight decrease in the energy efficiency in Annex B countries does not offset the effects of the reduction of the clinker rate and of the carbon intensity of the fuels used. Emissions per tonne of cement in Annex B countries decrease with the implementation of the climate policy: -12% in 2010 (600kg CO₂/tonne of cement vs. 680 in BaU), -14% in 2020 (570, 664) and -15% in 2030 (550, 647).

325. The intensity of this drop differs across the Annex B countries. It is higher in R&U, which turns out to have more technical flexibility.

Figure 46: No BTA / CO₂ emission per tonne of cement compared to BaU



326. Finally, in the No BTA scenario, variable production costs in Annex B countries increase in average by 9€ per tonne of cement after 2007 compared to BaU (+30%).

Figure 47: No BTA / Variable production cost of a tonne of cement compared to BaU

327. We notice that the gap between the variable production costs in BaU and in No BTA increases in Europe, Japan and Canada between 2010 and 2020. This is counter-intuitive since, adapting their technological and fuel choices to the introduction of an emission cost, the cement manufacturers of the Annex B should be able to diminish its level. This increase is actually due to the long-term fluctuations of the energy prices that the industrials do not foresight. In Japan for example, cement manufacturers switch a part of their fuel consumption from coal to WWF in the No BTA scenario, taking into account the cost of using a carbon intensive fuel. But around 2020, the price of WWF increases consequently compared to coal and the manufacturers are not able to switch back quickly from WWF to coal, because of the inertia of the combustion system. In BaU, Japanese cement manufacturers use WWF marginally and therefore are not impacted by the rise in their price around 2020.

328. It is worth noting that, from the production cost point of view, non Annex B countries benefit, although marginally, from the implementation of the climate policy in Annex B. Firstly because this policy leads to the decrease in the prices of the carbon intensive fuels. Indeed, these fuels are less used by Annex B countries. Secondly because, as we will see below, their production levels generally increase and a higher production level allows a faster resort to money-saving fuels or technologies.

REFERENCES

- Agence de l'Environnement et de la Maîtrise de l'Energie (**ADEME**): Approche expérimentale du bilan carbone d'une entreprise, Etude réalisée par MANICORE, contrat n°0010042. (2001)
- Armington**: A theory of demand for products distinguished by place of production, IMF Staff papers. (1969)
- Association Technique de l'Industrie des Liants Hydrauliques (**ATILH**): private communication, Didier LAFFAIRE. (2005).
- British Cement Association**: Memorandum by the British Cement Association, United Kingdom Parliament, European union Committee, available at <http://www.publications.parliament.uk/pa/ld200304/ldselect/ldecom/179/4050502.htm>. (2004)
- Brockhagen**: Distortion of competition in an international tradable allowances system, PhD thesis, CIREL. (2004)
- CEMBUREAU**: Best available techniques for the cement industry. A contribution from the European cement industry to the exchange of information and preparation of IPCC BAT reference document for the cement industry. (www.cembureau.com). (1999a)
- CEMBUREAU**: World Statistical Review no. 18 (1913-1995) and no 19-20 (1994-1995). (1999b)
- CEMBUREAU**: World Cement Directory 1996 & 2002. (2002)
- Ederington et al.**: Footloose and pollution free. National Bureau of Economic Research, WP9718. (2003)
- ECOFYS**: Energy Demand Side Technology Map: Industry, households, and services. (2002)
- Erkell-Rousse H. and Mirza D.**: Import price elasticities: reconsidering the evidence. Canadian Journal of Economics, 35(2): 282-306. (2002)
- European Commission (**EC**): Best available techniques reference document in the cement and lime manufacturing industries. European Integrated Pollution Prevention and Control Bureau (EIPPCB), IPTS, Sevilla, Spain. (2000)
- European Commission (**EC**): Decision 94/815/CE, Case IV/33.126 et 33.322 – Cement. (1994)
- Hendriks C.A., Worrel E., Jager D., Blok K., Reimer P.**: Emission reduction of greenhouse gases from the cement industry. Greenhouse Gas Control Technologies Conference Paper (www.ieagreen.org). (2000)
- Hoel M.**: Should a carbon tax be differentiated across sectors, Journal of public economics, 59(1), pp. 17-32. (1996)

- Hoerner J.A.:** The role of border tax adjustments in environmental taxation: Theory and U.S. experience, Presented at the International workshop on market based instruments and international trade of the Institute for environmental studies, Amsterdam, The Netherlands. (1998)
- Hourcade, J.-C., and Shukla P.:** Global, Regional, and National Costs and Ancillary Benefits of Mitigation, Chap. 8 in Climate Change 2001, IPCC Third Assessment Report, Cambridge UP. (2001)
- International Cement Review:** The Global Cement Report (third edition). (1998)
- International Energy Agency (**IEA**): The reduction of greenhouse gas emission from the cement industry. IEA Greenhouse Gas R&D Programme. (1999)
- International Energy Agency (**IEA**): Energy Statistics of OECD countries (2002a)
- International Energy Agency (**IEA**): Energy Statistics of Non OECD countries (2002b)
- International Energy Agency (**IEA**): Industrial Competitiveness under the European Union Emissions Trading Scheme, IEA Information paper, (2004)
- Ismer, R., and K. Neuhoff:** Border tax adjustments: A feasible way to address nonparticipation in emission trading, Cambridge Working Papers in Economics CWPE 0409 (2004)
- Johnson and Parkman:** Spatial monopoly, non-zero profits and entry deterrence: the case of cement, The Review of Economics and Statistics vol. 65, issue 3, pp. 431-39. (1983)
- La Cour, L. and H.P. Mollgaard:** Market domination: tests applied to the Danish cement industry", European Journal of Law and Economics, 14: pp. 99-127. (2002)
- LAFARGE:** Jean-Pierre TAILLARDAT, private communication. (2004)
- Lloyd:** Lloyd's List: Ports of the World. (2004)
- Mæstad, O.:** On the efficiency of green trade policies, Environmental and Resource Economics, 11: pp. 1-18. (1998)
- Majocchi, A. and M. Missaglia:** Environmental taxes and border tax adjustment, Conference Stato o Mercato? Intervento pubblico a architettura dei mercati, Pavia, Università, 5-6 ottobre. (2001)
- Markusen, J.:** International externalities and optimal tax structures, Journal of International Economics, 5: pp. 15--29. (1975)
- Ministère de l'Aménagement du Territoire et de l'Environnement (**MATE**): Circulaire du 15 avril 2002 relative aux modalités de contrôle par l'inspection des installations classées des bilans annuels des émissions de GES. Ministère de l'aménagement du territoire et de l'environnement. (2002)
- Mathiesen, L., and O. Mæstad:** Climate policy and the steel industry: achieving global emission reductions by an incomplete climate agreement, Discussion paper 20/02, Norwegian school of economics and business administration, Bergen, Norway. (2002)
- Quirion P.:** Allocation of CO₂ allowances and competitiveness: A case study on the European iron and steel industry. Presented at the 3rd CATEP workshop "global trading", Kiel, Germany. (2002)

Quirion, P. and J.-C. Hourcade: Does the CO₂ emission trading directive threaten the competitiveness of European industry? Quantification and comparison to exchange rates fluctuations, EAERE Annual Conference, June, Budapest. (2004)

Raspiller, S. and N. Riedinger: Do environmental regulations influence the location behavior of French firms?, EAERE Annual Conference, June, Budapest. (2004)

RIVM, Edgar database. (<http://arch.rivm.nl/env/int/coredata/edgar/intro.html>) (2001)

Sleich J. and Betz R: Incentives for energy efficiency and innovation in the European Emission Trading System, ECEEE Summer Study, Mandelieu, France, www.eceee.org. (2005)

Szabo L, Hidalgo I, Ciscar JC, Soria A, Russ P: Energy consumption and CO₂ emissions from the world cement industry. DG JRC-IPTS Report. Technical Report Series EUR 20769 EN. (2003)

Szabo L., Hidalgo I., Ciscar J.C. and Soria A.: CO₂ emission trading within the UE and Annex B countries: the cement industry case, Energy Policy, 34(1);99 pp. 72-87. (2006)

Ten Kate A. and Niels G.: To what extent are cost savings passed on to consumers? An oligopoly approach. (2004)

United Nations (UN): World Population Prospects: The 2002 Revision. Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat (<http://esa.un.org/unpp>). (2002)

United Nations (UN): World Urbanization Prospects: The 2001 Revision. Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat (<http://esa.un.org/unpp>). (2001)

Van Vuuren, D.P., Strengers, B.J., De Vries, H.J.M.: Long term perspectives on world metal use – a system dynamics model. Resources Policy 25, pp. 239-255. (1999)