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A SPATIAL COMPETITIVE ANALYSIS: THE CARBON LEAKAGE EFFECT ON THE CEMENT INDUSTRY UNDER THE EUROPEAN EMISSIONS TRADING SCHEME

by Elisabetta Allevi*, Giorgia Oggioni*, Rossana Riccardi* and Marco Rocco**

Abstract

The European Emissions Trading Scheme (ETS) is a cap and trade system to curb CO_2 emissions. It has caused both direct costs (CO_2 allowances) and indirect costs (higher electricity prices) to energy-intensive industries. Moreover, as there is no global CO_2 agreement, the ETS could distort the European economy, prompting energy-intensive industries to relocate production to unregulated countries: the "carbon leakage" effect. This paper investigates the impact of ETS on the cement industry, focusing on Italy, the second European producer, analyzing a Cournot oligopolistic partial equilibrium model with a detailed technological representation of the market. Simulation results show that the European and Italian cement markets are subject to carbon leakage, especially where carbon regulation is more stringent and where plants are located near the seacoast. Further, transportation costs - particularly high in the cement sector - significantly affect the rate of carbon leakage.

JEL Classification: C60, D43, D58, C61, Q50.
Keywords: carbon leakage, cement sector, ETS, generalized Nash game.

Contents

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1 Introduction[1]

Starting from a level of 594 million tons in 1970, the worldwide production of cement has more than quadruplicated in the past thirty years, reaching an amount of 3 million tons in 2009 (see Cembureau, 2009). This significant growth can be mainly ascribed to emerging countries. The two largest cement producers in the world are in fact China and India, followed by the US, Japan and Turkey and other Asian countries (see Cembureau, 2009). In Europe, the cement market is becoming mature. However, Italy, Spain, Germany and France still maintain significant cement production levels.

Since 2005, European cement industries are involved in the ETS. The ETS is a cap and trade system that introduces a price for each unit of CO_2 emitted by the combustion installations covered by the scheme. This may create costs, both direct and indirect, for the Energy Intensive Industries (EIIs) operating these installations. Both add up and affect EIIs; their impact depends on the industrial sector and they may change competition playing fields for carbon constrained sectors versus unconstrained competitors. The indirect cost (electricity cost) is due to the higher price of electricity that results from the pass-through of allowance (opportunity) costs in the price of electricity. The direct costs (CO_2 cost) accrue from the obligation to either buy allowances or reduce emissions in case emission allowances that are allocated for free (grandfathered) do not suffice to cover the realized emissions. This effect may be important for some sectors covered by the ETS (see Droege, 2011).

EIIs have argued that the ETS endangers their competitiveness with respect to companies of the same sectors located in environmentally less restrictive countries (see BUSINESSEUROPE, 2011). They also explain that they will progressively relocate some or all of their activities in these countries in order to protect their competitiveness. This would reduce emissions in Europe but increase them outside of the EU. This would result in no environmental benefit and could cost Europe significant economic and job losses. The expression "carbon-leakage" refers to this relocation of economic activities and emissions. The Intergovernmental Panel on Climate Change (IPCC) measures carbon leakage through a ratio that is defined as *"emission increase from a specific sector outside the country (as a result of the policy affecting that sector in the country) over the emission reductions in the sector (again as a result of the environmental policy)"*. Note that the sectors that are exposed to carbon leakage generally consist of multinational companies that operate worldwide and hence could relocate part of their production without suffering dramatic economic losses themselves. This is especially the case of metals and cement industries.

Several studies (Cook, 2011; Droege, 2011; McKinsey and Ecofys, 2006; Reinaud, 2005, 2008a, 2008b) show that these ETS impacts on industrial activity depend on several factors, namely *(i)* the industry's ability to pass the extra carbon cost onto the final consumer, *(ii)* the openness of international trade *(iii)* the energy intensity of the sector and its capability to abate carbon, *(iv)* the allowance allocation method and *(v)* the product specialization. These different factors combine to determine whether the sector is largely exposed to or protected from international competition. Service oriented economies will obviously suffer less from the ETS than those that heavily rely on highly emitting and energy intensive technologies. A recent Point Carbon survey (2010) based on interviews on European industrial sectors reveals that 41% and 38% of the consulted cement and metals companies have, at least, thought about moving production allegedly due to the carbon

[1]The authors are grateful to two anonymous referees and Ivan Faiella for very helpful comments and suggestions. The fourth author contributed to this work during his post-doctoral fellowship at the University of Bergamo (Italy). The views expressed are those of the authors and do not involve any responsibility of the Bank of Italy.

price. The figure on cement is also confirmed by Cook (2009), who finds that the carbon rate of cement industries is between 40% and 73%.

European cement industries have been amongst the most important supporters of the competitiveness and carbon leakage debate. The Boston Consulting Group (BCG) in 2008 estimated the ETS impacts on the European cement industry and analyzed how the carbon price can influence the decision of offshoring the clinker production, that accounts for 100% of cement's direct CO_2 emissions (Boston Consulting Group, 2008a). This study concludes that a CO_2 price higher than 35 €/ton would trigger a complete relocation of the EU cement industries by 2020. The outcome is still dramatic if one considers a carbon price of 25 €/ton: 80% of the EU clinker production is at risk of relocation by 2020. This percentage arises to 100% when considering European coastal countries, like Italy, Greece and Spain. These results are also confirmed by Reinaud (2008a, 2008b, 2009) who shows that cement sector can be interested by carbon leakage especially in the case of coastal plants and excess of capacity in unregulated countries. This means that the geographical distribution of EU plants is a relevant factor in relocation decisions. Cement and clinker are characterized by high transportation costs especially if land (road and rail) transport is used. Transport by ship is much cheaper and its economic efficiency increases with the distance. This explains the reason why coastal plants (and countries) have a bigger incentive to relocate their clinker/cement production than inland plants. Indeed, Italy and Spain are the largest importers of non-EU clinker and cement (see Droege, 2011). Import from non-EU countries is also facilitated by the uniformity of these products; so that consumers tend to be indifferent to where clinker and cement are produced, provided they are less expensive.

The need to protect the competitive position of the EU industry has accordingly been taken into account in the design of the Directive 2009/29/EC regulating the third ETS phase. More specifically, point 12 of Article 10a of this Directive states that "*in 2013 and in each subsequent year up to 2020, installations in sectors or subsectors which are exposed to a significant risk of carbon leakage shall be allocated, pursuant to paragraph 1, allowances free of charge at 100% of the quantity determined in accordance with the measures referred to in paragraph 1*".[2] This holds true for cement sector that is commonly deemed to be subject to the risk of carbon leakage, as the European Commission itself acknowledges.[3]

However, opinions diverge on the importance of carbon leakage. The "Climate Strategies group" (see Hourcade *et al.*, 2007) plays down the danger for Europe. The authors explain that iron and steel, aluminium, cement and lime are the only sectors that can be affected by the ETS; they study the UK and conclude that the problem is minor and particular solutions can probably be found. Even the allowance grandfathering has been considered a controversial measure. In its 2010 report, the Corporate Europe Observatory claims that energy intensive industries "*have lobbied EU institutions intensively to ensure they retain these benefits in the next phase of the ETS (2013-2020). By using threats of relocation and increased global emissions (carbon leakage), plus scaremongering about massive job losses, these industries have managed to ensure that the ETS will remain a way of providing significant subsidies for some of Europe's worst polluters*" through the allowance grandfathering system. This research also shows that "*Arcelor Mittal, Lafarge and other companies will have a huge surplus of CO_2 emissions permits at the end of the second phase of the EU's emissions trading scheme (ETS) in 2012, just as in phase one (2005- 2007).*" This surplus of free permits thus represents an

[2]Source: `http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0063:0087:en:PDF`

[3]See Commission Decision 24 December 2009, available at `http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:001:0010:0018:EN:PDF`

additional revenue that increases industries' profits. A recent report by Nomisma Energia (2012) highlights that the Italian cement sector gained around 265 million euros from selling unused free permits in the period 2008-2010. These figures are also confirmed by the comparison between the freely allocated allowances and the realized emissions of the European cement sector in the period 2008-2011 that shows an overallocation of grandfathered allowances.[4]

However, the gathering of free allowances may not suffice to fully compensate the carbon leakage effect on the cement sector. As indicated by Linares and Santamaria (2012) and Cook (2011), the allocation of free CO_2 permits may increase the profitability of cement companies without solving the problems of carbon leakage and reduced competitiveness. Taking stock of this evidence, this paper presents a "what if" analysis that, based on simulations, investigates the impact that an application of the ETS with binding caps (i.e., at odds with the current implementation of the scheme) might have on the Italian and, more in general, European cement sector.

In this connection, the major contribution of the present paper is the development of an international spatial oligopolistic model based on a technological representation of the cement market that describes the clinker and the cement production processes in different world countries in more detail than models in the literature do (see e.g. the process models recently developed by Soria and his team at IPTS;[5] see Szabó *et al.*, 2006).

Our analysis is more focused on the Italian market because of its possibly higher exposure to carbon leakage, but we also provide a representation of the European, Mediterranean and the Far Eastern cement markets. More specifically, we describe the technological structure of the major companies operating in Italy (and also at a worldwide level taking into account the kiln types used in the different sites).[6] We measure the carbon leakage exposure of ETS regulated countries (Italy and Europe) by monitoring their clinker exchanges with the Mediterranean and the Far East areas.

To be in line with the oligopolistic representation of the European cement market (provided also in other papers, such as Demailly and Quirion, 2008; Ghemawat and Thomas, 2008; Meunier and Ponssard, 2008, 2010; Ponssard and Walker, 2008; Ponssard, 2009; Walker, 2006), we assume that these companies are Cournot players. In this respect, another innovative feature of our model is that cement and carbon prices are endogenously determined.

The model is able to represent the interaction of cement companies that maximize their profit simultaneously, since their strategies are interrelated by the market clearing conditions, common to all the companies. This problem has been modeled as a non linear Generalized Nash Equilibrium Problem (GNEP) with jointly convex constraints. It is well known that a GNEP can have either no solution, or multiple solutions, or infinitely many solutions (see Facchinei and Pang, 2003, Facchinei and Kanzow, 2007 for a complete review). In this paper we guarantee the existence of an equilibrium solution. Moreover, taking into account the relationship between the solution of a GNEP and a Variational Inequality (VI) we reformulate and solve our model as a Complementarity Problem (CP), i.e. a particular instance of a VI.

The complementarity version of the model was implemented and solved in GAMS using the PATH solver. Apart from the cap values and transportation costs that we varied to generate different sce-

[4]See data published by the Community Independent Transaction Log (CITL) at `http://www.eea.europa.eu/data-and-maps/data/data-viewers/emissions-trading-viewer`.

[5]See `http://ipts.jrc.ec.europa.eu/`.

[6]The cement sector is highly concentrated. The cement industries operating in Italy are multinationals that control several plants around the world. It suffices to say that the multinational cement companies Holcim, Lafarge, Cemex, HeidelbergCement and Italcementi cover the 58% of the EU market and the 30% of global market (see Cook, 2011).

narios, we calibrated the remaining parameters based on publicly available data of cement producers belonging to European and non European countries, taking 2008 as the reference year.

Concerning the remainder of the paper, in Section 2 we describe the cement production process and present our mathematical model; Section 3 discusses the mathematical structure of the model, focusing in particular on existence results. Sections 4 and 5 are respectively devoted to the presentation of the case study under consideration and the obtained results. Finally, in Section 6 we report our final remarks.

2 The cement market model

In this section we provide the mathematical formulation of a spatial cement international trade model where cement companies are Cournot competitors. We recall that a typical process of cement manufacturing consists of three stages. There is first the extraction and the grinding of specific raw materials. These raw materials are then heated in kilns to produce clinker. In the third and last stage, clinker is cooled and milled with other additives in order to manufacture cement. The proportion and the type of additives change according to the kind of cement produced. Moreover, depending on the preparation of the raw materials and the technological characteristics of the kiln adopted, the process takes the name of wet, semi-wet, dry or semi-dry. Dry and semi-dry are more productive and require a lower amount of energy than the former two. Whatever the process adopted, clinker manufacturing releases to air nitrogen oxides (NO_x), sulphur dioxide (SO_2) and carbon dioxide (CO_2). CO_2 emissions are the by-products of the chemical conversion process used in the production of clinker that transforms limestone ($CaCO_3$), the raw material, into lime (CaO). Lime is then combined with silica, aluminum and iron-containing materials to have clinker. The thermal energy that these chemical reactions need is usually produced by burning carbon intensive fuels, like coal and pet-coke, that enhance carbon emissions. While CO_2 emissions coming from fuel burning can be reduced with the utilization of alternative fuels like biomass (see Cembureau, 1999 for a complete list), those generated by the conversion of limestone into lime are unavoidable. For this reason, emissions represent a cost for those cement industries operating in countries where stringent environmental regulations apply.

Taking into account the results by Reinaud (2008a, 2008b, 2009) and the study of the Boston Consulting Group (2008a), we divide the world cement industry in zones with and without environmental regulation, recalling that the risk of carbon leakage is incurred without any environmental benefit since emissions are not reduced but simply displaced from Europe to other places in the world. Each zone is further divided into regions (coastal and inland, in our case study) to better investigate the impact of regulation according to the geographical distribution of plants. Since the adopted technology can influence the amount of CO_2 emissions, a full description of the cement technological process is also provided. The technological process is split in clinker and cement production processes. Clinker can be produced with different technologies in full-cycle plants or bought from other competitors in the same zone or in different zones. Each company can then produce clinker for its own needs or sell it to other companies located in different zones. Companies compete in the market and we assume a time horizon of one year. During this period, it is assumed that companies operating in the market can not fail and there are no new entrants into the market. The ETS is also implemented in the spatial competition model. Cement price and emission allowances prices are endogenously determined in the model.

2.1 Notation

The notation that we use in the following is classified here on the basis of its meaning and the role it plays in the model.

A. Sets of Indices

A.1 General indices

$*\ C$	Cement companies operating in the market.
$*\ I$	Zones in which we can ideally divide the market, for the purpose of our analysis. In the following we will set $I = I_{ETS} \cup I_{NETS}$, where $I_{ETS} = \{1, \dots, \overline{m}\}$ will be the set of all zones that are subject to the ETS while $I_{NETS} = \{\overline{m}+1, \dots, n\}$ will stand for the set of those zones to which this scheme does not apply. Each zone $i \in I$ can be partitioned in r homogeneous regions, that we indicate by $i_1, i_2, \dots, i_r$ and we denote $Z_i = \{i_j : j \in J\}$, where $J = \{1, \dots, r\}$, for all $i \in I$. For example $j = 1, 2$ distinguish between coastal and inland regions in each zone $i \in I$.
$*\ U$	All possible technologies for the production of clinker.
$*\ V$	All possible technologies for the production of cement.
$*\ F$	Kinds of fuel employed in the production of clinker.

A.2 Company and zone dependent indices

$*\ K_{c,i_j}$	Plants of company $c \in C$ located in the region $i_j \in Z_i$, where $i \in I$ and $j \in J$.

A.3 Plant dependent indices

$*\ U_k$	Clinker technologies available in plant $k \in K_{c,i_j}$.
$*\ V_k$	Cement technologies available in plant $k \in K_{c,i_j}$.

Note that, given the hierarchical structure of our indexing, any plant-dependent quantity will automatically be company and zone-dependent as well, although we will not always underline this fact explicitly in our notation.

B. Parameters

B.1 Clinker related parameters

$*\ clkctr_{c,i_j,h_l}$	Marginal clinker transportation cost sustained by company $c \in C$ to move clinker from region $i_j \in Z_i$ to region $h_l \in Z_h$.
$*\ pstone_i$	Price of the stones (limestone, chalk, marl and shale) in zone $i \in I$ used as raw material for the production of clinker.
$*\ fuelprop_{f,i}$	Proportion of fuel $f \in F$ used in the clinker production in zone $i \in I$.
$*\ pfuel_f$	Price of fuel $f \in F$ used in the clinker production.

- α_u — Electricity consumption per tonnes of clinker produced with technology $u \in U$ (MWh/ton).
- cal_f — Caloric contribution of each fuel $f \in F$ used in the clinker production (MJ/ton).
- γ_u — Thermal consumption per tonnes of clinker produced with technology $u \in U$ (MJ/ton).
- $clkcap_{k,u}$ — Capacity of the kiln of technology $u \in U_k$ of plant $k \in K_{c,i_j}$.
- $pclk_i$ — Price of clinker for each zone $i \in I$ (euro/ton).

B.2 Cement related parameters

- $cmtctr_{c,i_j,h_l}$ — Marginal cement transportation cost sustained by company $c \in C$ to move cement from region $i_j \in Z_i$ to region $h_l \in Z_l$.
- $pmaterial_i$ — Price of the material (gypsum, slag, limestone) used in the production of cement in zone $i \in I$.
- $cmtcap_{k,v}$ — Grinding mill capacity of technology $v \in V_k$ of plant $k \in K_{c,i_j}$.
- β_v — Electricity consumption per tonnes of cement produced with technology $v \in V$ (MWh/ton).

B.3 Other parameters

- $pelectr_i$ — Average electricity price in zone $i \in I$.
- $GA_{k,u}$ — Amount of grandfathered allowances for plant $k \in K_{c,i_j}$ with technology $u \in U_k$, i.e. the quantity of emission allowances that plant k receives for free (ton/year).
- CAP — Total emission cap imposed in the market considered for cement plants covered by the ETS (ton/year).
- $\tau_{i,u}$ — Average emission factor per ton of clinker produced depending on the zone $i \in I$ and technology $u \in U$.

C. Variables

C.1 Clinker related variables

- $clkprod_{k,u}$ — Clinker produced by plant $k \in K_{c,i_j}$ with technology $u \in U_k$ (ton/year).
- $clksell_{c,i_j,\bar{c},h_l}$ — Clinker produced by company $c \in C$ in region $i_j \in Z_i$ and sold to company $\bar{c} \in C, \bar{c} \neq c$, in region $h_l \in Z_h$ (ton/year).
- $clkbuy_{c,i_j,\bar{c},h_l}$ — Clinker bought by company $c \in C$ to satisfy demand in region $i_j \in Z_i$ from company $\bar{c} \in C, \bar{c} \neq c$ in region $h_l \in Z_h$ (ton/year).
- $clkused_{c,i_j}$ — Clinker produced by company $c \in C$ in region $i_j \in Z_i$ and used in the same region (ton/year).
- $stone_k$ — Raw material (limestone, chalk, marl and shale) used by plant $k \in K_{c,i_j}$ to produce clinker (ton/year).
- $clkel_k$ — Electricity used by plant $k \in K_{c,i_j}$ to produce clinker (KWh/year).
- $fuel_{f,k,u}$ — Fuel of type $f \in F$ used by plant $k \in K_{c,i_j}$ to produce clinker with technology $u \in U_k$ (ton/year).

C.2 Cement related variables

- ∗ $cmtprod_{k,v}$ — Cement produced by plant $k \in K_{c,i_j}$ with technology $v \in V_k$ (ton/year).
- ∗ $cmtsell_{c,i_j,h_l}$ — Cement produced by company $c \in C$ in region $i_j \in Z_i$ and sold in region $h_l \in Z_h$ (ton/year).
- ∗ $cmtel_k$ — Electricity used by plant $k \in K_{c,i_j}$ to produce cement (KWh/year).
- ∗ $material_k$ — Material (gypsum, slag, limestone) used by plant $k \in K_{c,i_j}$ to produce cement (ton/year).

Note that all these variables are nonnegative, hence nonnegativity constraints for each one have to be introduced. Moreover, in the following subsections, we will indicate in parentheses, next to each constraint, the corresponding dual variable.

2.2 Clinker and cement producers' model under ETS environmental policy

We consider a static optimization problem, based on a time-window of one year, corresponding to the frequency at which the surrender of emission allowances is due. In this context, any cement company $\widehat{c} \in C$ faces the problem of maximizing its objective function $\theta_{\widehat{c}}$, subject to a set $\Xi_{\widehat{c}}$ of constraints, i.e.

$$(\mathcal{M}_{\widehat{c}}) \qquad \begin{array}{rl} \text{Max} & \theta_{\widehat{c}} \\ \text{s.t.} & \Xi_{\widehat{c}} \end{array}$$

Taking into account that the market structure in the cement industry is mainly oligopolistic, we provide the mathematical formulation of the producers' problem according to the hypothesis that suppliers can exercise the market power and alter the cement price by changing the amount they sell.

We then represent the model as a *Cournot* game among cement producers. In a Cournot game the cement price is endogenous in the model while in a perfect competition framework it is assumed to be exogenous. Let us define the endogenous regional price function as

$$p_{i_j} = p_{i_j}\left(\sum_{\substack{c \in C, \\ h_l \in Z_h, h \in I}} cmtsell_{c,h_l,i_j} \right), \quad i_j \in Z_i,\ i \in I \qquad (1)$$

The objective function of a reference producer $\widehat{c} \in C$ is defined as follows:

$$\theta_{\widehat{c}} = \sum_{h_l \in Z_h, h \in I} p_{h_l} \cdot \sum_{i \in I,\ i_j \in Z_i,} cmtsell_{\widehat{c},i_j,h_l} - \sum_{\substack{i,h \in I,\ i_j \in Z_i,\\ h_l \in Z_h}} cmtsell_{\widehat{c},i_j,h_l} \cdot cmtctr_{\widehat{c},i_j,h_l} \quad (2)$$

$$+ \sum_{\substack{i,h \in I,\ h_l \in Z_h,\\ i_j \in Z_i, c \in C, c \neq \widehat{c}}} pclk_h \cdot clksell_{\widehat{c},i_j,c,h_l} - \sum_{\substack{i,h \in I,\ h_l \in Z_h,\\ i_j \in Z_i, c \in C, c \neq \widehat{c}}} (pclk_i + clkctr_{\widehat{c},h_l,i_j}) \cdot clkbuy_{\widehat{c},i_j,c,h_l} \quad (3)$$

$$- \sum_{\substack{i \in I,\ i_j \in Z_i,\\ k \in K_{\widehat{c},i_j}}} pstone_i \cdot stone_k - \sum_{\substack{i \in I,\ i_j \in Z_i,\\ k \in K_{\widehat{c},i_j}}} pmaterial_i \cdot material_k \quad (4)$$

$$- \sum_{\substack{f \in F, i \in I,\ i_j \in Z_i,\\ k \in K_{\widehat{c},i_j}, u \in U_k,}} pfuel_f \cdot fuel_{f,k,u} - \sum_{\substack{i \in I,\ i_j \in Z_i,\\ k \in K_{\widehat{c},i_j}}} pelectr_i \cdot (clkel_k + cmtel_k) \quad (5)$$

$$+ \ pallow \cdot \sum_{\substack{i \in I_{ETS}, i_j \in Z_i,\\ k \in K_{\widehat{c},i_j}, u \in U_k}} (GA_{k,u} - \tau_{i,u} \cdot clkprod_{k,u}) \quad (6)$$

The economic interpretation of the addends that constitute $\theta_{\widehat{c}}$ is straightforward:

(2) defines the total producer $\widehat{c}$'s revenues from selling cement $cmtsell_{\widehat{c},i_j,h_l}$ at the destination price p_{h_l}. The revenues are net of the cement transportation costs $cmtsell_{\widehat{c},i_j,h_l} \cdot cmtctr_{\widehat{c},i_j,h_l}$;

(3) refers to clinker exchanges between company $\widehat{c}$ and another company c. In particular, accounts for both the revenues of selling clinker $pclk_h \cdot clksell_{\widehat{c},i_j,c,h_l}$ and the costs of buying clinker $(pclk_i + clkctr_{\widehat{c},h_l,i_j}) \cdot clkbuy_{\widehat{c},i_j,c,h_l}$. These costs also include the transportation charges;[7]

(4) stands for the expenses due to raw material employed respectively in the clinker ($pstone_i \cdot stone_k$) and in the cement ($pmaterial_i \cdot material_k$) production;

(5) records the energy component of the expenses (fuel and electricity). Costs $pfuel_f \cdot fuel_{f,k,u}$ refer to the fuel burnt in the kiln during the clinker production process; while $pelectr_i \cdot (clkel_k + cmtel_k)$ is the price charged for consuming electricity in milling clinker and cement;

(6) adds the opportunity cost of emission allowances whose price is $pallow$, as it will be explained in Section 2.3. In line with Directive 2003/87/EC and the disposals of Directive 2009/29/EC in matter of sectors exposed to carbon leakage risk, we assume that cement producers receive an amount of CO_2 permits for free ($GA_{k,u}$) that covers the CO_2 emissions ($\tau_{i,u} \cdot clkprod_{k,u}$) generated by the clinker production $clkprod_{k,u}$ according to an emission factor $\tau_{i,u}$ that we assume depending on zone i and technology u.

We now describe the set $\Xi_{\widehat{c}}$ of constraints for the maximization problem of company $\widehat{c} \in C$.

[7] In our model, we assume that transportation costs are charged to clinker buyers. For this reason, they are associated to the variable $clkbuy_{\widehat{c},i_j,c,h_l}$.

- **Non-negativity constraints**

All variables of problem $(\mathcal{M}_{\widehat{c}})$ have to be nonnegative.

- **Balance of cement production of company $\widehat{c}$ in region i_j**

Cement production of company $\widehat{c} \in C$ in region $i_j \in Z_i$ equals the sum of the quantity of cement that company $\widehat{c} \in C$ produces in region $i_j \in Z_i$ to sell in the same region $i_j \in Z_i$ and the quantity that company $\widehat{c}$ sells to regions $h_l \in Z_h$ with $h_l \neq i_j$.

$$\sum_{k \in K_{\widehat{c},i_j}, v \in V_k} cmtprod_{k,v} = \sum_{h \in I, h_l \in Z_h} cmtsell_{\widehat{c},i_j,h_l} \qquad (\lambda cmtprod_{\widehat{c},i_j}) \tag{7}$$

- **Tonnes of raw materials used by plant k to produce cement**

According to our references (see Cembureau, 1999, European Commission, 2010, and Ponssard and Walker, 2008) cement is composed of 0.8 of clinker and 0.2 of other materials, like gyspum, slag and limestone as stated by equality (8). The raw materials required by plant $k \in K_{\widehat{c},i_j}$ are:

$$material_k = 0.2 \cdot \sum_{v \in V_k} cmtprod_{k,v} \qquad (\lambda material_k) \tag{8}$$

- **Balance of clinker produced by company $\widehat{c}$ in region i_j**

The following balance specifies that the quantity of clinker produced by company $\widehat{c} \in C$ in region $i_j \in Z_i$ is equal to the sum of the quantity it uses in cement production in the same region $(clkused_{\widehat{c},i_j})$ and the amount of clinker it sells to the other companies $(clksell_{\widehat{c},i_j,c,h_l})$.

$$\sum_{k \in K_{\widehat{c},i_j}, u \in U_k} clkprod_{k,u} = clkused_{\widehat{c},i_j} + \sum_{\substack{c \in C, c \neq \widehat{c} \\ h \in I, h_l \in Z_h}} clksell_{\widehat{c},i_j,c,h_l} \qquad (\lambda clksell_{\widehat{c},i_j}) \tag{9}$$

- **Balance of clinker demanded by company $\widehat{c}$**

The following balance specifies that the sum of the quantity of clinker bought by company $\widehat{c} \in C$ and the sum of clinker produced and used in each region $i_j \in Z_i$ is equal to the amount needed for cement manufacturing according to the proportion required.

$$\sum_{i \in I, i_j \in Z_i} clkused_{\widehat{c},i_j} + \sum_{\substack{c \in C, c \neq \widehat{c} \\ i \in I, i_j \in Z_i \\ h \in I, h_l \in Z_h}} clkbuy_{\widehat{c},i_j,c,h_l} = 0.8 \cdot \sum_{\substack{i \in I, i_j \in Z_i \\ k \in K_{\widehat{c},i_j}, v \in V_k}} cmtprod_{k,v} \qquad (\lambda clkbuy_{\widehat{c}}) \tag{10}$$

Notice that the first term of equation (10) is the sum of the clinker production of company $\widehat{c}$ and the clinker bought by company $\widehat{c}$ from all the other competitors in order to satisfy internal clinker demand.

- **Clinker trade balance**

The following balance specifies that the quantity of clinker sold by company $c' \in C$ in region $i_j \in Z_i$ to company $c \in C$, $c \neq c'$, in region $h_l \in Z_h$ is equal to the quantity of clinker that company $c \in C$ buys from company $\widehat{c} \in C$.

$$clkbuy_{c,h_l,c',i_j} = clksell_{c',i_j,c,h_l}, \qquad c \neq c' \qquad (\lambda clktrade_{c',i_j,c,h_l}) \tag{11}$$

- **Regional clinker balance**

The following balance specifies that the demand of clinker in region $i_j \in Z_i$ is equal to the sum between clinker used in zone $i_j \in Z_i$ and the amount bought from the other regions.

$$0.8 \cdot \sum_{\substack{c \in C, k \in K_{c,i_j}, \\ v \in V}} cmtprod_{k,v} = \sum_{c \in C} clkused_{c,i_j} + \sum_{\substack{c, \bar{c} \in C, c \neq \bar{c}, \\ h \in I, h_l \in Z_h}} clkbuy_{c,i_j,\bar{c},h_l} \qquad (\lambda clkbalance_{i_j}) \tag{12}$$

- **Capacity constraints of the kiln of technology u of plant k**

Condition (13) imposes the capacity constraints on clinker production of technology $u \in U_k$ of plant $k \in K_{\widehat{c},i_j}$.

$$clkcap_{k,u} - clkprod_{k,u} \geq 0 \qquad (\lambda clkcap_{k,u}) \tag{13}$$

- **Capacity constraints of grinding mill of technology v of plant k**

Condition (14) imposes the capacity constraint on cement production of technology $v \in V_k$ of plant $k \in K_{\widehat{c},i_j}$.

$$cmtcap_{k,v} - cmtprod_{k,v} \geq 0 \qquad (\lambda cmtcap_{k,v}) \tag{14}$$

- **Tonnes of raw materials used by plant k to produce the tonnes of clinker needed**

Following our references (Cembureau, 1999, and European Commission, 2010), a kiln in average burns 1.57 tonnes of raw material (limestone, chalk, marl and shale) to produce a tonne of clinker. Condition (15) defines this mass balance.

$$stone_k = 1.57 \cdot \sum_{u \in U_k} clkprod_{k,u} \qquad (\lambda stone_k) \tag{15}$$

- **Electricity needed by plant k to produce cement and clinker**

The consumption of electricity mainly derives from the milling phases and depends on the kiln and the technology chosen at each stage. Equation (16) defines the electricity consumption in plant $k \in K_{\widehat{c},i_j}$ for clinker production. Notice that α_u represents the marginal electricity consumption per tonne of clinker produced with technology $u \in U_k$.

$$clkel_k = \sum_{u \in U_k} \alpha_u \cdot clkprod_{k,u} \qquad (\lambda clkel_k) \tag{16}$$

Equation (17) defines the electricity consumption in plant k for cement production. Notice that β_v represents the marginal electricity consumption per tonne of cement produced with technology $v \in V_k$.

$$cmtel_k = \sum_{v \in V_k} \beta_v \cdot cmtprod_{k,v} \qquad (\lambda cmtel_k) \tag{17}$$

- **Amount of fuel f used by plant k with technology u to produce clinker**

Equation (18) defines fuel f consumption in plant $k \in K_{\widehat{c},i_j}$ for clinker production. Notice that γ_u represents the marginal thermal consumption per tonne of clinker produced with technology $u \in U_k$ and $fuelprop_{f,i}$ is the proportion of fuel $f \in F$ used in clinker production in zone $i \in I$.

$$fuel_{f,k,u} = \frac{fuelprop_{f,i} \cdot \gamma_u}{cal_f} \cdot clkprod_{k,u} \qquad (\lambda fuel_{f,k,u}) \tag{18}$$

2.3 Emissions constraint

The production activity of each company may be restricted by the emission limits imposed by the ETS. The emission constraint (19) concerns the cement sector only and defines a cap on the CO_2 generated by clinker production. The dual variable *pallow* to which it is associated can be interpreted as the allowance price.[8] In this model, we assume that companies are price-takers in the emission market (as it includes several sectors, with the cement sector accounting only for approximately 5% of total emissions), while they may influence the cement price (the cement market is highly concentrated).

The sum of the emissions generated by the cement plants located in zones $i \in I_{ETS}$ (that, in our case, are covered by the ETS) cannot exceed the total emission cap CAP defined for cement in these zones.

$$CAP - \left(\sum_{\substack{c \in C, i \in I_{ETS}, i_j \in Z_i, \\ k \in K_{c,i_j}, u \in U_k}} \tau_{i,u} \cdot clkprod_{k,u} \right) \geq 0 \qquad (pallow) \tag{19}$$

Notice that the dual variable *pallow* is positive when the constraint is strictly binding.

3 Mathematical structure

Let X be a nonempty, closed and convex subset of the n-dimensional Euclidean space $\mathbb{R}^n$ and $F : X \to \mathbb{R}^n$ a continuous mapping. The variational inequality problem (VI for short) is the problem

[8]Note that this price is only a proxy of the price observed in the emission market, as we do not explicitly model other industrial sectors.

of finding a point $x^* \in X$ such that

$$F(x^*)^\top (x - x^*) \geq 0, \quad \forall\, x \in X, \tag{20}$$

where we denote by $F(x^*)^\top$ the transpose of $F(x^*)$.[9] The solution set of VI (20) is denoted by $SOL(X, F)$.

Most existence results of solutions for VIs are proved by using various fixed point theorems. For instance, it is well known that, as a consequence of Brouwer fixed point theorem, VI (20) has a solution if X is compact and F is continuous.

Theorem 1 *(Hartman and Stampacchia, 1966) If X is a nonempty, compact and convex set and F is continuous on X, then VI (20) admits at least one solution.*

In general, a VI can have more than one solution. Theorem 3 below recalls a condition under which VI (20) has a unique solution; this result needs a generalized monotonicity assumption.

Definition 1 *Let X be a convex set in $\mathbb{R}^n$. A mapping $F : X \subseteq \mathbb{R}^n \to \mathbb{R}^n$ is said to be*

- monotone *on X if $(F(x) - F(y))^\top (x - y) \geqslant 0$, $\forall x, y \in X$;*
- strictly monotone *on X if $(F(x) - F(y))^\top (x - y) > 0$, $\forall x, y \in X$ and $x \neq y$.*

For a continuosly differentiable mapping $F : X \to \mathbb{R}^n$, we recall the following well-known monotonicity criteria, where ∇F denotes the matrix that has as its i-th column the gradient of F_i, ∇F_i.

Theorem 2 *(Ortega and Rheinboldt, 1970) Let X be an open convex set in $\mathbb{R}^n$ and let $F : X \subseteq \mathbb{R}^n \to \mathbb{R}^n$ be countinuously differentiable on X.*

- *F is monotone on X if and only if ∇F is positive semidefinite on X;*
- *F is strictly monotone on X if ∇F is positive definite on X.*

Under assumptions of monotonicity of F and compactness of the set X, we can establish existence and uniqueness of the solutions of a VI.

Theorem 3 *(Harker and Pang, 1990) If F is strictly monotone, then VI (20) has at most one solution.*

VIs are closely related to many problems of Nonlinear Analysis, such as complementarity, fixed point and optimization problems. A complementarity problem (CP) is problem (20) in the case where X is a cone. In particular, when $X = \mathbb{R}^n_+$, the non-negative orthant of $\mathbb{R}^n$, the CP is the problem of finding a point x^* such that:

$$0 \leq x^* \perp F(x^*) \geq 0, \tag{21}$$

where $F : \mathbb{R}^n_+ \to \mathbb{R}^n$. We recall that condition (21) can be explicitly written as:

$$x^* \geq 0, \qquad F(x^*) \geq 0, \qquad F(x^*)^\top x^* = 0. \tag{22}$$

[9] See Nagurney (1999) for a detailed presentation of VIs and their use in economic modeling.

Let us now consider a Generalized Nash Equilibrium Problem (GNEP) with N players. Let $x^\nu \in \mathbb{R}^{n_\nu}$, $\nu = 1, \ldots, N$, denote the variables controlled by player ν and $\mathbf{x} = \big((x^1)^\top, (x^2)^\top, \ldots, (x^N)^\top\big)^\top$ be the vector of all decision variables (see Facchinei and Kanzow, 2007 for a complete review on the topic). Let us also denote by $\mathbf{x}^{-\nu}$ the vector formed by all players' decision variables except those of player ν.

The problem of player $\nu \in \{1, \ldots, N\}$, given the other players' strategies, is to solve:

$$\begin{aligned} \min_{x^\nu} \; & f_v(x^\nu, \mathbf{x}^{-\nu}) \\ \text{sub to } & x^\nu \in X_\nu(\mathbf{x}^{-\nu}) \end{aligned} \tag{23}$$

where f_v is the cost function of player ν and $X_\nu(\mathbf{x}^{-\nu}) \in \mathbb{R}^{n_\nu}$ is the set of strategies depending on the rival players' strategies, $\mathbf{x}^{-\nu}$. For any $\mathbf{x}^{-\nu}$, the solution set of problem (23) is denoted by $\mathcal{S}_\nu(\mathbf{x}^{-\nu})$. The GNEP can be defined as follows.

Definition 2 *The GNEP is the problem of finding a vector $\bar{\mathbf{x}}$ such that*

$$\bar{x}^\nu \in \mathcal{S}_\nu(\bar{\mathbf{x}}^{-\nu}), \qquad \forall \nu \in \{1, \ldots, N\}.$$

The GNEP can be interpreted as the problem of finding a vector of equilibrium strategies for all players $\nu = 1, \ldots, N$, where the feasible region of each player is defined by two sets of constraints: the set of constraints only depending on decision variables of player ν and the set of common constraints. In electricity markets, for instance, common constraints arise in modeling transmission lines capacities. Equilibria of GNEPs, however, are extremely difficult to compute. A particular case is that of jointly convex common constraints. We recall that jointly convex common constraints mean that the (convex) feasible sets of all players still depend on the rivals' strategies, but are the same for all players. More precisely, we assume that there is a common strategy space $\mathbf{X} \subseteq \mathbb{R}^n$, $n = \sum_\nu n_\nu$ such that the feasible set of player $\nu = 1, \ldots, N$ is given by

$$X_\nu(\mathbf{x}^{-\nu}) = \{x^\nu : (x^\nu, \mathbf{x}^{-\nu}) \in \mathbf{X}\} \tag{24}$$

Theoretical results show that, under the assumption of jointly convex constraints, there exist equilibria of GNEPs that are also solutions to particular Variational Inequalities (VIs) and viceversa. The following theorem (see Facchinei *et al.*, 2007) highlights the relationship between the solution of a VI and the solutions of a GNEP. Recall that a function $f : \mathbb{R}^p \to \mathbb{R}$ is called pseudo-convex on a set $K \subseteq \mathbb{R}^p$ if there exists an open superset A of K such that f is continuously differentiable on A and, for all $x, y \in A$,

$$\nabla f(x)^\top (y - x) \geq 0 \quad \Longrightarrow \quad f(y) \geq f(x).$$

Theorem 4 *(Facchinei et al., 2007) Let us suppose that the GNEP satisfies the following assumptions for all $\nu = 1, \ldots, N$:*

i) for every player $\nu \in N$, f_ν is continuously differentiable in $\mathbf{x}$;

ii) for every player $\nu \in N$, f_ν, the function $f_\nu(\cdot, \mathbf{x}^{-\nu})$ is pseudo-convex in x^ν;

iii) the feasible set of player ν can be written as $X_\nu(\mathbf{x}^{-\nu}) = \{x^\nu : (x^\nu, \mathbf{x}^{-\nu}) \in \mathbf{X}\}$, with $\mathbf{X}$ closed and convex.

Then, every solution of the VI$(\mathbf{X},\mathbf{F})$ is a solution of the GNEP, where $\mathbf{F}:\mathbb{R}^n \to \mathbb{R}^n$ is defined as follows:

$$\mathbf{F}(\mathbf{x}) = \left(\nabla_{x^1} f_1(\mathbf{x})^\top, \nabla_{x^2} f_2(\mathbf{x})^\top, \ldots, \nabla_{x^N} f_N(\mathbf{x})^\top\right)^\top.$$

Theorem 4 states that a solution of a VI is also a solution of a GNEP. In this light, existence results for the solutions of a VI also ensure existence of equilibria in the GNEP. An existence result for a GNEP complying with the set-up of Theorem 4 is stated in the following result, which combines Theorems 1 and 4.

Corollary 1 *Let assumptions i), ii), iii) of Theorem 4 hold and let $\mathbf{F}$ as well be defined as in Theorem 4. Furthermore, suppose that the set $\mathbf{X}$ is compact. Then a solution of VI$(\mathbf{X},\mathbf{F})$ exists and this is also a solution of the corresponding GNEP.*

A tighter relation between the solution sets of VIs and GNEPs can be derived in the particular case where $\mathbf{X}$ is defined as follows:

$$\mathbf{X} = \{\mathbf{x} \in \mathbb{R}^n : g(\mathbf{x}) \leq 0\}, \tag{25}$$

with $n = \sum_{\nu=1}^N n_\nu$, where n_ν is the dimension of the decision variables of player ν, and $g:\mathbb{R}^n \to \mathbb{R}^m$ is such that $g_i:\mathbb{R}^n \to \mathbb{R}$ is convex and continuously differentiable for all $i = 1,\ldots,m$.
Suppose also that $\mathbf{x}$ is a solution of the GNEP. Then the following classical Karush-Kuhn-Tucker (KKT) conditions are satisfied for each player $\nu = 1,\ldots,N$:

$$\nabla_{x^\nu} f(x^\nu, \mathbf{x}^{-\nu}) + \nabla_{x^\nu} g(x^\nu, \mathbf{x}^{-\nu})\lambda^\nu = 0, \qquad 0 \leq \lambda^\nu \perp g(x^\nu, \mathbf{x}^{-\nu}) \leq 0, \tag{26}$$

where $\lambda^\nu \in \mathbb{R}^m$ is a vector of multipliers. The KKT conditions for VI$(\mathbf{X},\mathbf{F})$ are the following:

$$\mathbf{F}(\mathbf{x}) + \nabla_{\mathbf{x}} g(\mathbf{x})\lambda = 0, \qquad 0 \leq \lambda \perp g(\mathbf{x}) \leq 0, \tag{27}$$

where $\lambda \in \mathbb{R}^m$ is a vector of multipliers.

The following theorem, among the solutions of a GNEP, characterizes those that are also VI's solutions.

Theorem 5 *(Facchinei et al., 2007) Let us suppose that the GNEP satisfies assumptions i), ii) and iii) of Theorem 4 and the set $\mathbf{X}$ is given by (25). Vector $\mathbf{x}$ is a solution of VI$(\mathbf{X},\mathbf{F})$ at which the KKT conditions (27) hold if and only if $\mathbf{x}$ is a solution of the GNEP at which KKT conditions (26) hold with $\lambda^1 = \cdots = \lambda^N = \lambda$.*

The model we proposed in the previous section may be rewritten as a GNEP with jointly convex constraints as in (25). When implementing the model, we will assume that the zonal price function is affine and decreasing. Under this additional assumption, rewriting the problem of each company as a minimization problem, it is easy to verify that the objective functions $-\theta_c,\ c \in C$, are continuously differentiable and convex (quadratic or linear) in all variables that depend on company c and the set $\mathbf{X}$, that includes all the companies constraints, is nonempty, convex and compact. As a consequence, according to Corollary 1, we can ensure that our GNEP admits at least one solution. According to these properties, the complementarity version of the problem, that is more suitable for computational purposes and is presented in Appendix A, provides a variational solution of the original model.

4 Case study

The database collects the data of cement producers belonging to European and non European countries taking 2008 as reference year. The focus of our analysis is on the Italian cement sector for which we have a complete mapping of all cement and clinker installations, but we also consider the cement sector of other three geographical zones respectively represented by Europe, the Mediterranean area and the Far East. The description of the cement market of these three regions is based on the data of the most representative, in terms of cement production, countries located in these regions. For selecting these representative countries, we referred to the Cembureau annual report (Cembureau, 2009) that gives a list of the major cement producers at a worldwide level. More specifically, the European cement market is proxied on the basis of the Spanish, German and French cement sector data. To describe the Mediterranean cement sector, we take as reference the Turkish and the Egyptian ones and, finally, India and China are used to represent the cement industries in the Far East. The market analyzed is stylized in Figure 1. Each company can have more than one plant in regulated and/or unregulated zones. Each company competes in the international trade market selling and buying clinker and cement within the intra-regional and inter-regional market.

Our aim is to analyze the cement/clinker exchange between regulated (Italy and Europe) and unregulated (Mediterranean area and Far East) zones in order to evaluate the possible carbon leakage effect under different scenarios. Globally we consider eighty cement plants separated into coastal

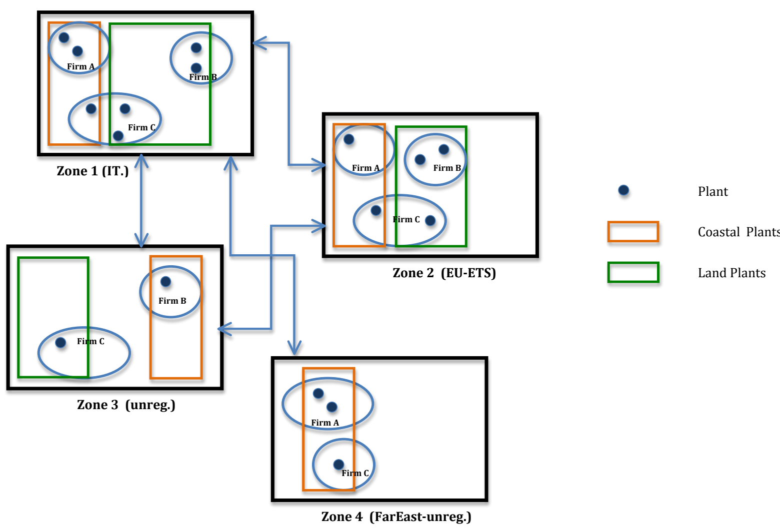

Figure 1: The case of Four different zones and three firms

and inland plants that are run by six main cement companies, namely Italcementi, Buzzi, Holcim, Cal.Me, Colacem, Cementir.[10] We select these companies because they represent 70% of the Italian market. Apart from Cal.Me, these are multinational industries operating at a worldwide level both in the regulated and unregulated zones (Figure 1 depicts the sample case of three firms). In addition, we consider a fringe composed of the other small companies operating in each region of this market.

[10]The considered plants include both integrated plants that produce both clinker and cement and a few cement mills that produce cement using clinker from other installations.

Each plant is characterized by its clinker and cement capacity and technology. We consider three different clinker technologies: wet, semi-dry and dry and each plant of the integrated process can dispose of one of these technologies. Portland cement is the homogeneous final output and we assume the adoption of a unique technology for producing it. This assumption is not restrictive since the technology for producing cement is well established and the energy and emission intensive phase of the production process is clinker production. For each company and plant, clinker and cement capacities have been estimated taking into account data provided by company's websites.[11] Operation costs, input consumption and emission factors are strictly dependent on the adopted technology and plants' location. Table 1 reports data on prices taking 2008 as reference year. All the data provided in the table (raw materials, fuels and electricity prices) have been estimated from Eurostat database.[12] Data on conversion factors (electricity consumption, fuel consumption, materials) are available in European Commission (2010).

Table 1: Raw Materials, fuels and electricity prices: baseline 2008

Input price/ Zone	**Stones (€/t)**	**Coal (€/t)**	**Petcoke (€/t)**	**Altern. Fuels (€/t)**	**Clinker (€/t)**	**Electricity (€/MWh)**
Italy	3.75	87	69	6.5	54	71
Europe	3.13	80	65	6.5	58	57
Mediterran.	1.56	60	50	6.5	35	46
Far East	1.56	40	35	6.5	28	46

Table 2 reports the data related to fuel proportions per zone. It can be easily observed that countries without environmental regulation have no incentive in substituting pollutant fuels with alternative ones in order to reduce the impact on the environment.

Table 2: Fuel proportions in different zones

Fuel prop./ Zone	**Coal**	**Petcoke**	**Alternative Fuels**
Italy	82%	14%	4%
Europe	48%	34%	18%
Mediterran.	20%	79%	1%
Far East	6%	94%	0%

Zonal cement demand is formulated with an affine inverse demand function; demand parameters (zonal reference price and consumption) are estimated using data provided by Eurostat.[13] Most existing studies therefore indicate that cement demand is highly inelastic to price. Taking into account the reference literature on this subject (see Cook, 2011, Droege, 2011, Meunier and Ponssard, 2008, Demailly and Quirion, 2006, 2008), we set cement demand elasticity at 0.2.[14] Clinker zonal demand

[11] For an exhaustive description of data sources see Appendix A.

[12] Source: `http://epp.eurostat.ec.europa.eu/portal/page/portal/statistics/search_database`.

[13] Source: `http://epp.eurostat.ec.europa.eu/portal/page/portal/statistics/search_database`.

[14] Small perturbations of this parameter preserving inelasticity of the demand do not significantly affect our results.

is determined as a function of the zonal cement production (see Section 2) while clinker prices are exogenous and computed on the basis of Eurostat database. We model the ETS to test whether and how the environmental regulation can influence cement and clinker production decisions. As indicated in Section 2, the ETS is modeled by means of a constraint that limits the CO_2 emissions generated by clinker production that causes 100% of cement direct carbon emissions. We restrict the emission market to the European cement sector only and we analyze two main CO_2 cap scenarios (in addition to the case without any cap) as indicated in Section 5. Since almost all of the kilns operating at European level use dry technologies we assume a uniform CO_2 emission factor of 0.875 per ton of clinker produced, as indicated in Ponssard and Walker (2008). We recall that dry technology is the more efficient technology in energy consumption and there is no incentive to change for wet and semi-dry processes.

We conduct a sensitivity analysis on transportation costs that, as already explained in Section 1, strongly affect the cement and clinker exchanges and prices. The transportation costs of cement are around 20% higher than those of clinker and their amount varies according to the type of transport used (see Boston Consulting Group, 2008b). In addition, the geographical distribution of cement and clinker plants matters not only because the transportation costs are lower for coastal plants but also because the distance that cement and clinker exchanges can cover depends on the type of transport used. For instance, the distance between a producing plant and a consumer can not be greater than 300 Km when cement is delivered by land (road and/or rail). This makes the cement market, especially for inland plants, quite regional. This is not the case for the coastal plants that can be reached also by sea and thus are more open to international markets (see Droege, 2011).

Finally, since we do not account for investment policies, we assume that, for each plant, the investment costs have been fully amortized. We leave this kind of analysis for future research.

5 Results

In this section, we provide the main results of our analysis. As highlighted in the previous section, we investigate the cement market trade by varying transportation costs. To this aim, we compare three different scenarios:

Case 1. In this scenario, we assume that transportation costs both from/to Far East region and Mediterranean area are high.

Case 2. In this scenario, we assume that transportation costs from/to Far East region are high while those from/to Mediterranean area are low.

Case 3. In this scenario, we assume that transportation costs both from/to Far East region and Mediterranean area are low.

For each of these cases, we adopt three different CO_2 emission policies (all of them differ from the current implementation of the ETS):

- **NO Cap**: This case assumes no ETS regulation;
- **Cap 80**: This case, with regulation, imposes a 80 Mtons CO_2 cap on cement CO_2 emissions. We estimate this cap on the basis of the clinker production in the market studied in 2008.

- **Cap 50**: This case considers a more restrictive regulation. The cap imposed on emissions generated in regulated countries is of 50 Mtons.[15]

Notice that, the computation of the CO_2 cap is based on clinker production and not on the data of the National Allocation Plans (NAPs) of the cement plants installed in the regulated countries, namely Italy, Spain, Germany and France, in order to avoid allowance overallocation. Our goal is to analyze if a relatively restrictive allowance grandfathering system can mitigate or prevent the carbon leakage effect. In other words, we assume that the CO_2 market is more stringent than it has actually been for the last few years and will probably be in the third phase of the European ETS (2013-2020). In particular, we assume that the ratio of granfathered allowances to caps is 90%, a figure in line with the directives for the second ETS phase[16] and more restrictive compared to the impositions of Directive 2009/29/EC for the third phase.

Our scope is to analyze the possible carbon leakage effect on the Italian and the European cement markets considering all these hypotheses. As already said, clinker production is 100% responsible for the direct CO_2 emissions of the cement process and thus producers could be more interested in relocating clinker kilns. For this reason, we measure only the carbon leakage rate on clinker production and we define it as the ratio between the increase of EU regulated countries' clinker imports from non-EU areas and the reduction in coastal and inland clinker production in EU regulated countries. The increase in clinker imports in EU regulated countries is computed as the difference between their amount before and after the application of the ETS. Similarly, the decrease in clinker production in EU regulated countries results from the comparison between their levels before and after the ETS. In other words, the carbon leakage rate in the *Cap 80* case is computed using the following ratio:

$$\frac{(\textit{NO Cap} - \textit{Cap 80})\ \textbf{imports}}{(\textit{NO Cap} - \textit{Cap 80})\ \textbf{production}}$$

For the *Cap 50* case the carbon leakage rate becomes:

$$\frac{(\textit{NO Cap} - \textit{Cap 50})\ \textbf{imports}}{(\textit{NO Cap} - \textit{Cap 50})\ \textbf{production}}$$

Note that, since in our analysis we do not account for the labour costs or any cyclical factors, the variations in clinker and cement production can be only ascribed to transportation costs and environmental regulation.[17] The Section is organized as follows: we first report the results on the Italian cement market according to the different scenarios presented above; then we focus our attention on the European case and finally we compare profits results in the different cases.

5.1 Effects of the ETS on the Italian cement market

Tables 3, 4 and 5 report the main results concerning the Italian cement market under the transportation cost and emission market assumptions illustrated above. A first consideration is that,

[15]Note that this cap is particularly restrictive for cement sector. This can be interpreted as a possible step towards the decarbonization of the European cement sector.

[16]However, Cap 80 and Cap 50 are more restrictive than those really imposed in the first two ETS phases. This implies that, in our simulations, the amount of permits freely allocated are lower.

[17]In the period 2009-2012, there has been a contraction of the cement/clinker production and consumption due to the economic crisis. However, in our analysis we do not account for this scenario.

independently of the transportation freights, the Italian cement market is exposed to carbon leakage and its exposure rate is higher for the coastal zones. This means that the geography plays an important role in this market.

In Table 3, we compare the three emission regulation scenarios (*NO Cap*, *Cap 80*, *Cap 50*) presented in the previous Section under the transportation assumptions of *Case 1*. The comparison between the *NO Cap* and the two *Cap* scenarios shows that the emission regulation increases the cement price.[18] This means that cement producers are able to transfer part of their direct carbon costs to the final cement price. Moreover, this increase is more significant in the *Cap 50* case, where a more restrictive CO_2 ceiling leads to an emission price of 53.64 €/ton, compared to 32.5 €/ton of the *Cap 80* case. The backside effect of this "cost pass through" is the contraction of the (Italian and European) cement demand and, consequently, of clinker consumption. This effect is highlighted by the results reported in Tables 3, 4 and 5 (see row "IT clinker consumed") that show a drastic decrease of the Italian clinker consumption in presence of the ETS compared to the *NO Cap* case. Note that this shrinkage is higher when the carbon policy becomes more restrictive.[19]

The key factor in this analysis is the trend of clinker imports. As shown in Table 3 these imports from NO-EU countries cover 10% of the total clinker demand in Italy when *NO Cap* applies. This proportion exponentially increases when the ETS applies. Note that under the transportation assumptions of *Case 1*, Italian cement producers prefer importing clinker from the Far East rather than from the Mediterranean area. This apparently surprising results find an explanation in the current trend of the cement market. In fact, the imports from Turkey have been declining since 2003 when the domestic demand of clinker/cement production started to increase as a consequence of the economic growth of this country. Initially, this gap was filled in by imports from Egypt but now imports come from China, that disposes of a capacity surplus and has a relatively weak currency (see Cook, 2011).

This means that Italian cement producers find more attractive the Far East market than the Mediterranean one. In all ETS scenarios, imports are destined to cover part of the coastal cement demand. This proportion is relatively low in absence of regulation (18% of the coastal demand, compared to a 10% of the overall cement Italian consumption), but it becomes 100% when the ETS applies (51% of the total Italian consumption). It is important to highlight that the levels of these coastal imports are not affected by the cap imposed on the CO_2 emissions. The amount of non-Italian clinker used to cover the relative Italian demand is reported in row "NO-IT clinker consumed". In all CO_2 regulation scenarios, this clinker is devoted to coastal use.

As a consequence, while in the *NO Cap* case, the clinker produced in Italy is almost equally distributed between inland and coastal plants, in both the *Cap 80* and *Cap 50* scenarios, the Italian clinker production is totally destined to inland plants (see row "IT clinker consumed"). The inland plants use national clinker because its price (including also transportation costs) is lower than that of the imported clinker. In fact, coastal plants face only the sea freights, while the inland plants have to pay the road freights, that are very expensive. This reduces the economic convenience of the foreign clinker and makes the local clinker more attractive.

These results can be easily interpreted in terms of carbon leakage whose rate is 100% and 91% respectively in the *Cap 80* and *Cap 50* scenarios. The carbon leakage effect depends on the clinker

[18]Note that the inland cement prices are higher than the coastal prices because they include higher transportations costs.

[19]In Table 3, the total Italian clinker consumption in the *NO Cap* case is 35.43 Mtons and it drops to 18.68 Mtons and 17.09 Mtons respectively in the *Cap 80* and *Cap 50* scenarios when the ETS applies. Note that the ETS effects on clinker consumption are independent of the transportation cost assumptions as one can see from Tables 4 and 5.

movements towards the Italian coastal area.[20]

When considering *Case 2* analyzed in Table 4, we have some modifications in the clinker import flows. First the clinker imports are lower in the *NO Cap* case than in the other two cases with CO_2 regulation. This implies that, with carbon restrictions, cement companies increase their use of clinker coming from non-EU countries to reduce their emission costs. Second, in line with the previous results, the total non-IT clinker consumed increases as the CO_2 cap tightens. In other words, the amount of imported clinker in *Cap 50* is higher than in *Cap 80.* Considering the foreign clinker provenience, one can see that the Italian coastal plants continue to consume clinker from the Far East, while inland plants cover a small proportion of their clinker demand with the imports from the Mediterranean zone. However, note that the amount of clinker coming from the Mediterranean countries is relatively low, because, as explained above, they have first to satisfy their growing internal demand (see Table 4).

This happens because the transportation costs from/to this area are lower than in *Case 1.* In fact, both in *Cap 80* and *Cap 50* scenarios, the foreign clinker imports are split between coastal and inland areas. This does not happen in the *NO Cap* case where all imported clinker covers the coastal demand. In *Case 2*, a carbon leakage phenomenon is still in place, mainly due to imports to the coastal zone, but it is smaller than in *Case 1.* In fact, the carbon leakage rate amounts to 17% and 20% respectively in the *Cap 80* and *Cap 50* scenarios. This can be explained by the fact that, even without ETS, the imports from no-IT countries are relatively high. In particular, cement companies' imports in the *NO Cap* case are around 19.00 Mtons against the 3.80 Mtons of the respective scenario in *Case 1.*

Case 3 is the most extreme case of our analysis because it assumes that the transportation costs from/to the Mediterranean area and from/to the Far East are relatively low. Under these assumptions, the clinker imports of inland Italian plants from the Mediterranean area are replaced with imports from the Far East (see Table 5 for the results). The Italian coastal clinker demand is totally covered by imports from the Far East. This happens both with and without the application of the ETS. This means that there exists a threshold for the transportation costs under which the application of an environmental policy does not affect the strategies of cement companies operating coastal plants. For this companies, it is economically convenient to transfer their clinker production outside and this decision is taken independently of the ETS implementation. Under this assumption, the coastal plants are not subject to any carbon leakage because the relocation of production activities is completed before the enter in force of a CO_2 regulation. The situation for the inland plants is different: they are not relocated but produce cement using imported clinker if the ETS applies (compare *NO Cap* with *Cap 80* and *Cap 50*). The higher is the carbon emission restriction and the higher is their proportion of imported clinker.

Our analysis shows that the transportation costs strongly affect the carbon leakage phenomenon both in terms of the amount of production relocation and of involved areas.

[20] As already observed, the contraction of the Italian clinker demand, and thus of national clinker production, is higher under the CO_2 assumption of the *Cap 50* scenario. Since the clinker import levels in *Cap 80* and *Cap 50* are identical, our definition of carbon leakage leads to a lower ratio in the *Cap 50* case.

Table 3: Main results of Case 1 for the Italian cement market

	Case 1: Transportation costs high from/to both the Far-East and the Mediterranean area								
	NO Cap			Cap 80			Cap 50		
	IT-Coastal	IT-Inland	IT-Total	IT-Coastal	IT-Inland	IT-Total	IT-Coastal	IT-Inland	IT-Total
Cement price (€/ton)	105.22	121.64		108.66	124.90		115.70	131.87	
CO_2 price (€/ton)	-	-	-	32.5	32.5		53.64	53.64	
Clinker import rate Far-East	18%	-	10%	100%	-	52%	100%	-	52%
Clinker import rate Med	-	-	-	-	-	-	-	-	-
IT clinker consumed (Mtons)	16.75	18.68	35.43	-	18.68	18.68	-	17.09	17.09
NO-IT clinker consumed (Mtons)	3.80	-	3.80	20.55	-	20.55	20.55	-	20.55
Clinker carbon leakage rate						**100%**			**91%**

Table 4: Main results of Case 2 for the Italian cement market

	Case 2: Transportation costs high from/to the Far-East, low from/to the Mediterranean area								
	NO Cap			Cap 80			Cap 50		
	IT-Coastal	IT-Inland	IT-Total	IT-Coastal	IT-Inland	IT-Total	IT-Coastal	IT-Inland	IT-Total
Cement price (€/ton)	99.92	116.18		106.80	123.10		114.00	118.07	
CO_2 price (€/ton)	-	-		38.40	38.40		60.14	-	
Clinker import rate Far-East	92%	-	48%	100%	-	52%	100%	-	52%
Clinker import rate Med	-	-	-	-	9%	4%	-	12%	6%
IT clinker consumed (Mtons)	1.55	18.68	20.23	-	17.03	17.03	-	16.44	16.44
NO-IT clinker consumed (Mtons)	19.00	-	19.00	20.55	1.65	22.20	20.55	2.24	22.79
Clinker carbon leakage rate						**17%**			**20%**

Table 5: Main results of Case 3 for the Italian cement market

	Case 3: Transportation costs low from/to both the Far-East and the Mediterranean area								
	NO Cap			Cap 80			Cap 50		
	IT-Coastal	IT-Inland	IT-Total	IT-Coastal	IT-Inland	IT-Total	IT-Coastal	IT-Inland	IT-Total
Cement price (€/ton)	119.26	134.33		125.59	140.66		132.13	147.19	
CO_2 price (€/ton)	-	-		77.97	77.97		100.49	100.49	
Clinker import rate Far-East	100%	-	52%	100%	41%	72%	100%	62%	82%
Clinker import rate Med	-	-	-	-	-	-	-	-	-
IT clinker consumed (Mtons)	-	18.68	18.68	-	11.11	11.11	-	7.13	7.13
NO-IT clinker consumed (Mtons)	20.55	-	20.55	20.55	7.57	28.12	20.55	11.55	32.09
Clinker carbon leakage rate						**31%**			**41%**

5.2 Effects of the ETS on the European cement market

In this section, we discuss the ETS effects on the European cement market. For these ETS regulated zones, the results show a trend slightly different from the Italian market. As noted for the Italian cement market, European coastal regions are more exposed to carbon leakage effects. The clinker import rates, however, are, in general, lower than those of the Italian case. Inland located plants decide to produce clinker in the same region both with and without emission regulation, while coastal regions import clinker and their importing rate depends on the transportation costs level. Decisions on clinker import are mainly affected by the ETS: in all the three cases reported in Tables 6, 7 and 8, the *Cap 50* determines the highest import rates.

When considering *Case 1*, under both *Cap 80* and *Cap 50* policy scenarios, the carbon leakage value is 64%. This value has to be compared with the modified situation in clinker demand. Indeed, the clinker import rates significantly vary among the different regimes. The decision of increasing import quantities from Far-East regions is partially mitigated by the contraction of clinker consumption. In absence of regulation, clinker consumption is about 90.5 million tons and significantly drops to 73 millions in case of *Cap 50*.

Taking into account the results of Table 7, it can be seen that the reduction of transportation costs from and to the Mediterranean area does not modify the decision of importing from Far-East countries. The amount of imported clinker, however, slightly decreases both in the case of *Cap 80* and *Cap 50*.

Finally, the third case presented in Table 8 highlights a different behavior. When transportation costs are low both in the Mediterranean area and in the Far-East countries, the carbon leakage rates are the highest among the three cases (87% with *Cap 50*). Inland regions decide to import clinker from Far-East countries and the cement price reaches the values of 152.40 euros in case of tighter environmental constraints. As suggested from the analysis of the Italian market, the European cement companies are able to pass through part of the cost of CO_2 allowances on the cement price.

Table 6: Main results of Case 1 for the European cement market

	Case 1: Transportation costs high both in the Far-East and in the Mediterranean area								
	NO regulation			ETS cap = 80 Mtons			ETS cap = 50 Mtons		
	EU-Coastal	EU-Inland	EU-Total	EU-Coastal	EU-Inland	EU-Total	EU-Coastal	EU-Inland	EU-Total
Cement price (€/ton)	115.09	134.28		118.55	137.74		125.87	144.93	
CO_2 price (€/ton)	-	-		32.5	32.5		53.64	53.64	
Clinker import rate Far-East	5%	-	2%	36%	-	17%	97%	-	83%
Clinker import rate Med	-	-	-	-	-	-	-	-	-
EU clinker consumed (Mtons)	32.48	56.81	89.29	21.82	50.93	72.75	0.99	39.06	40.05
NO-EU clinker consumed (Mtons)	1.56	-	1.56	12.22	-	12.22	33.05	-	33.05
Clinker carbon leakage rate						**64%**			**64%**

Table 7: Main results of Case 2 for the European cement market

	Case 2: Transportation costs high from/to the Far-East, low from/to the Mediterranean area								
	NO Cap			Cap 80			Cap 50		
	EU-Coastal	EU-Inland	EU-Total	EU-Coastal	EU-Inland	EU-Total	EU-Coastal	EU-Inland	EU-Total
Cement price (€/ton)	106.29	123.00		113.17	129.91		120.37	137.11	
CO_2 price (€/ton)	-	-		38.40	38.40		60.14	60.14	
Clinker import rate Far-East	5%	-		31%	-	12%	95%	-	38%
Clinker import rate Med	-	-		-	-	-	-	-	-
EU clinker consumed (Mtons)	32.48	56.81	89.29	23.47	50.93	74.40	1.65	39.06	40.70
NO-EU clinker consumed (Mtons)	1.56	-	1.56	10.58	-	10.58	32.40	-	32.40
Clinker carbon leakage rate						**61%**			**63%**

Table 8: Main results of Case 3 for the European cement market

	Case 3: Transportation costs low from/to both the Far-East and the Mediterranean area								
	NO Cap			Cap 80			Cap 50		
	EU-Coastal	EU-Inland	EU-Total	EU-Coastal	EU-Inland	EU-Total	EU-Coastal	EU-Inland	EU-Total
Cement price (€/ton)	124.00	139.42		130.34	145.76		136.98	152.40	
CO_2 price (€/ton)	-	-		77.97	77.97		100.49	100.49	
Clinker import rate Far-East	-	3%	2%	22%	5%	12%	70%	21%	39%
Clinker import rate Med	-	-	-	-	-	-	-	-	-
EU clinker consumed (Mtons)	34.05	55.24	89.29	26.62	53.70	80.32	10.11	39.91	50.01
NO-EU clinker consumed (Mtons)	-	1.56	1.56	7.42	3.10	10.53	23.94	11.92	35.86
Clinker carbon leakage rate						**100%**			**87%**

5.3 Profit analysis

The profit analysis is conducted for the cement sector only and is based on the results of our simulations. The companies' global profits are reported in Table 9 and are detailed by component. In particular, we consider the revenues generated by the selling of cement and clinker (see rows "RevenueCEM" and "RevenueCLK" respectively), the sources of costs related to the clinker and cement production processes, namely electricity, fuel and raw material consumptions (rows "CostElectr", "CostFuel" and "CostMaterial")[21] and the costs of importing clinker (row "CostCLKbuy"). In addition, we consider the transport component (row "CostTrasp")[22] and the emission opportunity costs ("AllowanceGain").

Cases 1, 2 and 3 present similar trends as far as the "RevenueCEM" is concerned. In all cases, revenues accruing from selling cement increase when the carbon regulation applies. This can be mainly ascribed to the raise of cement prices due to the ETS. In fact, the ETS reduces cement production, but the variations resulting from the comparison of *No Cap* with *Cap 80* and *Cap 50* scenarios are relatively low. Considering first the cement production variations between the *No Cap* and *Cap 80* scenarios, one can see that in *Case 1*, the amount of cement produced in the *No Cap* scenario is 580 Mtons that decrease by 2% when *Cap 80* is applied reaching a level of 570 Mtons. One faces a similar tendency in *Case 2*, where the cement production before and after the regulation is of 590 and 570 Mtons respectively corresponding to a cut of 3%. Finally, in *Case 3*, the cement production cut is still around 3%: from a level of 609 Mtons it falls to 589 Mtons. When comparing *No Cap* with *Cap 50* scenarios, cuts are slightly higher: they become -5.5% (548 Mtons), -7% (548Mtons) and -7% (567 Mtons) respectively in *Case 1*, *Case 2* and *Case 3*. The cement revenues assume their highest value in the *Cap 50* case where the allowance price is always higher than in the corresponding *Cap 80* case. Note that this trend on cement revenues is also reflected in the "CostTrasp" that in the *Cap 80* and *Cap 50* are always lower than in the case without ETS. As already said, the ETS causes a reduction of cement demand and thus also of the cement exchanges. This decrease is higher under the *Cap 50* assumption and, in fact, the transport costs, in this case, are always lower than in the *Cap 80*.[23]

The allowance prices also affect the "AllowanceGain" is always positive and guarantees a revenue to the cement companies.[24] Since our analysis departs from the overallocation of free permits actually observed, the "AllowanceGain" positivity can be ascribed to carbon leakage on clinker. In fact, companies operating plants in Europe import clinker from unregulated countries. In this way, they do not use part of the grandfathered allowances that can be sold on the CO_2 market.[25]

Another interesting component of the companies' profits is "CostCLKbuy", the costs of buying clinker. The clinker acquiring costs are significantly affected by the scenarios on transport costs. While, in *Case 1*, "CostCLKbuy" is higher in the *Cap 80* and *Cap 50* scenarios compared to the situation without emission regulation, in *Cases 2 and 3* it happens exactly the reverse. We recall

[21]"CostElectr" encompasses the costs of consuming electricity both in the clinker and cement production phases; "CostFuel" is related to the costs of the fuel burned in the kilns; "CostMaterial" is the cost of buying raw materials used both in the clinker and cement production phases.

[22]The transportation costs refers to the costs of cement exchanges only. The transportation costs of clinker are directly included in the "CostCLKbuy" term because transport costs significantly affect zonal clinker prices.

[23]This result may appear in contrast with the revenues accruing from selling cement that are higher in the *Cap 50* compared to the *Cap 80* level. But one has to keep in mind that carbon costs, reflected in the cement prices, are higher when emission constraints are more restrictive, as it is case for *Cap 50*.

[24]Note that "AllowanceGain" accounts for the whole area covered by the ETS, namely Italy and Europe.

[25]We do not explicitly model the other sectors involved in the ETS, but we assume that companies can sell permits that they do not use to cover their emissions.

that the ETS burdens have a double effect on clinker: on one side, they lead to a reduction of the cement production and consequently of the clinker demand, but, on the other side, induces coastal plants to import clinker from non-regulated countries (and especially from China, which has excess production capacity). Depending on the *Case* at hand and on the transportation costs, one effect prevails on the other and gives the trend described above.

Overall, our simulations indicate an increase in profits for the cement sector stemming from the introduction of the emission permits trading scheme. This result is a consequence of both some features of the model (e.g., no border tax adjustment on clinker imports and exogenous prices for all inputs of production) and the assumptions on the emission market itself. Indeed, this market is cross-sector, allowing, for instance, cement companies to modify their production strategies and sell unused free emission permits to companies in other sectors.

Table 9: Profit analysis

	Case 1: high transp. costs			**Case 2: high in the Far-East**			**Case 3: low transp. costs**		
Revenue/Costs (Ml Euro)	No Cap	Cap 80	Cap 50	No Cap	Cap 80	Cap 50	No Cap	Cap 80	Cap 50
RevenueCEM	69.600	70.173	71.166	68.116	69.320	70.317	69.413	70.800	71.961
RevenueCLK	5.244	5.810	5.563	6.600	5.714	5.556	6.739	5.666	5.310
CostElectr	4.210	4.087	3.895	4.274	4.085	3.898	4.406	4.207	4.023
CostFuel	2.647	2.445	2.253	2.681	2.445	2.252	2.751	2.502	2.293
CostMaterial	1.717	1.593	1.452	1.738	1.591	1.453	1.783	1.630	1.491
CostCLKbuy	8.933	10.162	9.813	11.092	10.026	9.793	8.216	6.878	6.455
CostTrasp	12.496	11.644	9.882	11.418	10.036	8.440	6.836	6.437	6.020
AllowanceGain	-	7.152	13.416	-	8.452	15.044	-	17.164	25.136
Profit	**44.840**	**53.204**	**62.850**	**43.513**	**55.302**	**65.080**	**52.160**	**71.977**	**82.123**

6 Conclusions

This paper proposes a spatial equilibrium model for analyzing the carbon leakage effect on the European cement market under different scenarios of ETS regulation. In particular, we adopt a technological representation of the international cement market that covers Europe, with a particular emphasis on the Italian market, the Mediterranean area and Far East countries. Cement and clinker production processes are fully modeled in order to capture effects of the ETS on both production decisions. Clinker is the main source of direct CO_2 emissions and countries under environmental regulations can decide to import clinker quantities from unregulated regions for accomplishing with emission limits. Clinker imports mainly depend on transportation costs: inland plants suffer from higher transportation costs than the coastal ones. For this reason, we classify production sites in coastal and inland plants and provide full computational tests by varying transportation costs. In addition, we consider three different environmental scenarios: the first scenario represents the case of absence of regulation; the other two describe the emission regulation with restrictive caps (recall that these scenarios depart from the present implementation of the ETS, which overallocates emission permits to cement companies). Under our assumptions, the analysis shows that the Italian and the European cement markets are exposed to carbon leakage and this exposure is higher for coastal plants especially when the regulation is more stringent. Carbon leakage regards clinker production and it is strongly affected by transportation costs. By comparing the Italian market and other European markets, Italy is more exposed and this depends on the location of its plants that are mainly installed in coastal areas. In this respect, our results are broadly consistent with the literature that addresses the possibility of carbon leakage even when allowances are grandfathered. This means that, under the assumptions described in Section 5, an implementation of the ETS with sufficiently restrictive caps might lead to a market distortion that would induce companies to reduce their CO_2 emissions in regulated countries by importing clinker (when economically convenient) from unregulated areas and to sell the spare free allowances in order to increase their profits. The raise of this market distortion would open new perspectives for the introduction of more sophisticated regulatory mechanisms that could limit it.

A Complementarity version of the clinker and cement producer problem

In this appendix we describe the mixed complementarity formulation of problem $\mathcal{M}_{\widehat{c}}$ presented in Section 2.2.[26] Note that the complementarity formulation of the clinker and cement producers' model lead to a mixed complementarity problem because, in addition to the complementarity conditions associated to non-negative variables and inequality constraints, there are also the equality constraints (7), (8), (9), (10), (11), (12), (15), (16), (17), (18) that are combined with free variables. Note that we here report only the complementarity conditions, while we refer to Section 2.2 for the equality constraints. See also Section 3 for the definition and the notation of complementarity condition.

- **Clinker complementarity conditions**

$$0 \leq -\lambda clksell_{\widehat{c},i_j} + 1.57 \cdot \lambda stone_k + \alpha_u \cdot \lambda clkel_k + \gamma_u \cdot \sum_{f \in F} \frac{fuelprop_{f,i}}{cal_f} \cdot \lambda fuel_{f,k,u} \tag{28}$$
$$+\lambda clkcap_{k,u} + \tau_{i,u} \cdot pallow \perp clkprod_{k,u} \geq 0, \quad \forall \;\; i \in I_{ETS},\; i_j \in Z_i,\; k \in K_{\widehat{c},i_j}, u \in U_k$$

$$0 \leq -\lambda clksell_{\widehat{c},i_j} + 1.57 \cdot \lambda stone_k + \alpha_u \cdot \lambda clkel_k + \gamma_u \cdot \sum_{f \in F} \frac{fuelprop_{f,i}}{cal_f} \cdot \lambda fuel_{f,k,u} \tag{29}$$
$$+\lambda clkcap_{k,u} \perp clkprod_{k,u} \geq 0, \quad \forall \;\; i \in I_{NETS},\; i_j \in Z_i,\; k \in K_{\widehat{c},i_j}, u \in U_k$$

$$0 \leq -pclk_h + \lambda clktrade_{\widehat{c},i_j,c,h_l} + \lambda clksell_{\widehat{c},i_j} \perp clksell_{\widehat{c},i_j,c,h_l} \geq 0, \tag{30}$$
$$\forall \;\; i, h \in I,\; i_j \in Z_i,\; h_l \in Z_h,\; c \in C,\; c \neq \widehat{c}$$

$$0 \leq \lambda clkbalance_{i_j} + \lambda clksell_{\widehat{c},i_j} - \lambda clkbuy_{\widehat{c}} \perp clkused_{\widehat{c},i_j} \geq 0, \qquad \forall \;\; i \in I,\; i_j \in Z_i \tag{31}$$

$$0 \leq \lambda clkbalance_{i_j} + pclk_i + clkctr_{\widehat{c},h_l,i_j} - \lambda clktrade_{c,h_l,\widehat{c},i_j} - \lambda clkbuy_{\widehat{c}} \perp clkbuy_{\widehat{c},i_j,c,h_l} \geq 0, \tag{32}$$
$$\forall\, i \in I, h \in I,\; i_j \in Z_i,\; h_l \in Z_h,\; c \in C, c \neq \widehat{c}$$

$$0 \leq pstone_i - \lambda stone_k \perp stone_k \geq 0, \quad \forall\, i \in I,\; i_j \in Z_i,\; k \in K_{\widehat{c},i_j} \tag{33}$$

$$0 \leq pelectr_i - \lambda clkel_k \perp clkel_k \geq 0, \quad \forall\, i \in I,\; i_j \in Z_i,\; k \in K_{\widehat{c},i_j} \tag{34}$$

$$0 \leq pfuel_f - \lambda fuel_{f,k,u} \perp fuel_{f,k,u} \geq 0, \quad \forall\, i \in I,\; i_j \in Z_i,\; k \in K_{\widehat{c},i_j},\; u \in U_k,\; f \in F \tag{35}$$

[26] See Gabriel *et al.* (2012) for a detailed presentation of mixed complementarity problems and their utilization in modeling energy markets.

- **Cement complementarity conditions**

$$0 \leq -\lambda cmtprod_{\widehat{c},i_j} + 0.8 \cdot \lambda clkbuy_{\widehat{c}} + 0.2 \cdot \lambda material_k + \beta_v \cdot \lambda cmtel_k + \tag{36}$$
$$-0.8 \cdot \lambda clkbalance_{i_j} + \lambda cmtcap_{k,v} \perp cmtprod_{k,v} \geq 0, \quad \forall\, i \in I,\ i_j \in Z_i,\ k \in K_{\widehat{c},i_j},\ v \in V_k$$

$$0 \leq pmaterial_i - \lambda material_k \perp material_k \geq 0, \quad \forall\, i \in I,\ i_j \in Z_i,\ k \in K_{\widehat{c},i_j} \tag{37}$$

$$0 \leq pelectr_i - \lambda cmtel_k \perp cmtel_k \geq 0, \quad \forall\, i \in I,\ i_j \in Z_i,\ k \in K_{\widehat{c},i_j} \tag{38}$$

$$0 \leq -p_{h_l} - \frac{\partial p_{h_l}}{\partial cmtsell_{\widehat{c},i_j,h_l}} \cdot \sum_{\substack{g \in I,\ g_m \in Z_g,\\ h_p \in Z_h}} cmtsell_{\widehat{c},g_m,h_p} + cmtctr_{\widehat{c},i_j,h_l} \tag{39}$$
$$+\lambda cmtprod_{\widehat{c},i_j} \perp cmtsell_{\widehat{c},i_j,h_l} \geq 0 \quad \forall\, i \in I,\ i_j \in Z_i,\ k \in K_{\widehat{c},i_j}$$

Notice that in the complementarity version the balance of the emission market constraints requires that the following inequality hold:

- **Emission market complementarity condition**

$$0 \leq CAP - \left(\sum_{\substack{c \in C, i \in I_{ETS}, i_j \in Z_i,\\ k \in K_{c,i_j}, u \in U_k}} \tau_{i,u} \cdot clkprod_{k,u} \right) \perp pallow \geq 0 \tag{40}$$

- **Other conditions**

$$0 \leq clkcap_{k,u} - clkprod_{k,u} \perp \lambda clkcap_{k,u} \geq 0, \quad \forall\, i \in I,\ i_j \in Z_i,\ k \in K_{\widehat{c},i_j},\ u \in U_k \tag{41}$$

$$0 \leq cmtcap_{k,v} - cmtprod_{k,v} \perp \lambda cmtcap_{k,v} \geq 0, \quad \forall\, i \in I,\ i_j \in Z_i,\ k \in K_{\widehat{c},i_j},\ v \in V_k \tag{42}$$

B Database sources

In this appendix, the main web sources for our database construction are collected. These are provided by every single country, and general information on the cement industry is also indicated.

Cement Industry

The European Cement Association (CEMBUREAU) http://www.cembureau.be/

World Business Council for Sustainable Development (WBCSD). *Cement Sustainability Initiative (CSI)* http://www.wbcsdcement.org/

United Nations Commodity Trade Statistics Database (UN Comtrade).
http://comtrade.un.org/db/default.aspx

Eurostat Database.
http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home

Organisation for Economic Co-operation and Development (OECD) employment database.
http://www.oecd.org/document/34/0,3343,en 2649 39023495 40917154 1 1 1 1,00.html

European Pollutant Emission Register.
http://ec.europa.eu/environment/ets/welcome.do

China

Tsinghua University of China. *Assisting Developing Country Climate Negotiators through Analysis and Dialogue: Report of Energy Saving and CO_2 Emission Reduction Analysis in China Cement Industry*. 2008. Available at:
http://www.ccap.org/docs/resources/694/China Cement Sector Case Study.pdf

Price, L. *Prospects for Efficiency Improvements in China's Cement Sector*. 2006. Presentation at the "Cement Energy Efficiency Workshop". Available at:
http://www.iea.org/work/2006/cement/Price.pdf

WWF. *A blueprint for a climate friendly cement industry*. Available at:
http://assets.panda.org/downloads/englishsummary__lr_pdf.pdf

Tongbo, S. *A brief on China Cement Status Towards A Sustainable Industry*. 2010. Presentation at the "IEA-BEE International Workshop on Industrial Energy Efficiency". Available at:
http://www.iea.org/work/2006/cement/Price.pdf

Taylor, M., C. Tam and D. Gielen. *Energy Efficiency and CO_2 Emissions from the Global Cement Industry*. 2006. Available at:
http://www.iea.org/work/2006/cement/taylor_background.pdf

France

Cimbeton. *Infociments. Rapport Annuel*. 2008.
Available at: http://www.infociments.fr/publications/industrie-cimentiere/rapports-activite/ra-g03-2008

Further information are available at: http://www.infociments.fr/publications

Germany

BDZ Deutsche Zementindustrie. *Zement-Jahresbericht. Bundesverband der Deutschen Zementindustrie e.V.* 2009-2010.
Available at:
http://www.bdzement.de/fileadmin/gruppen/bdz/1Presse_Veranstaltung/Jahresberichte/BDZ-Jahresbericht_08_09.pdf

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