Università di Pisa
Dipartimento di Statistica e Matematica
Applicata all'Economia

Report n. 344

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Pisa, 11 gennaio 2011
- Stampato in Proprio –

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Evaluating the efficiency of the cement sector in presence of undesirable output: a world based Data Envelopment Analysis

G. Oggioni* R. Riccardi† R. Toninelli‡

Abstract

Cement industry is an energy intensive industry. Coal combustion and calcination of limestone and magnesium carbonate in kilns, in the clinker sub-process, generate a considerable amount of CO_2 as undesirable factor. In this paper, we provide an efficiency measure for twenty-one worldwide countries within a production framework of both desirable and undesirable factors. We try to answer to the following questions: do undesirable factors modify the efficiency levels of cement industry? Is it reasonable to omit CO_2 emissions in evaluating the performances of the cement sector in different countries? In order to answer to these questions, alternative formulations of standard Data Envelopment Analysis model and directional distance function are compared both in presence and in absence of undesirable factors. Two instances are investigated in order to assess the efficiency of cement industry: the first one considers the whole cement production process while the second one is focused on the clinker sub-process, the main responsible of CO_2 emissions. The results show that efficiency levels vary if we include or omit undesirable factors. Efficiency levels are influenced by investments in best available technologies and by the utilization of alternative fuels and raw materials in cement and clinker production processes. Among considered countries, a significant difference in efficiency scores between the two instances is obtained when blended cements are produced.

Key words: Data Envelopment Analysis, undesirable output, environmental regulation.
AMS - 2000 Math. Subj. Class. 90C05, 90C90, 90C31, 90C32.
JEL - 1999 Class. Syst. C14, C61, D24.

1 Introduction

Used in building and in civil engineering constructions, cement is at the basis of the economic development of a country. Starting from a figure of 594 million tons in 1970, the worldwide production of cement is quadruplicated in the last twenty-five years, reaching an amount of 2,284 million tons in 2005 (see [29]). In 2009, despite the global economic crisis, the worldwide production of cement

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increased by 6.4% towards 2008 up to 3 million tons (see Cembureau [4]). This growth was mainly due to China and India, the two largest cement producers in the world[1]. Other leading countries in cement production are the USA, Japan and Turkey. Even European countries, like Italy, Spain, Germany, France have a significant cement production that contributes to the cement global demand.

Cement is the result of a long production process beginning with the extraction of specific raw materials from quarries, continuing with the intermediate production of clinker in specific kilns and concluding with the grinding of clinker with additives whose quantity varies according to the type of cement produced[2]. The most commonly used type of cement is Portland that is the main constituent of concrete and other types of cement, like blastfurnace, pozzolanic and composite cements. Four main processes can be applied to manufacture cement: dry, wet, semi-dry and semi-wet. Their application depends on the state of the available raw materials. Dry and semi-dry processes are generally more productive and require a lower amount of energy than the other two. In Europe, the 90% of the clinker production is based on dry and semi-dry processes, while worldwide wet processes remain the most commonly adopted (see [10]). However, it is worthwhile to highlight the efforts of developing countries, like China and India, to invest in new and efficient technologies to replace old, inefficient production sites. The efficiency of the cement manufacturing process depends on clinker production.

Clinker production is the core of cement manufacturing, but it is also a very energy and intensive production phase in terms of (NO_x, SO_2, CO_2) emissions. The production of each ton of clinker requires, on average, 1.52 ton of raw materials (see [10]). In particular, clinker results from the combination of the so-called calcination and clinkering sub-production steps. Calcination consists, at a temperature of 900 Celsius degrees, in a decomposition of the calcium carbonate ($CaCO_3$) into calcium oxide (CaO or lime) and carbon dioxide (CO_2) that is liberated into the atmosphere. The calcium oxide is then burnt at a temperature of about 1,450 Celsius degrees with silica, aluminum and iron oxides in kilns that differs according to the process adopted. The huge quantity of thermal energy needed for these chemical reactions is usually generated by burning highly emitting fuels (coal and pet-coke), even though less emitting alternative fuels, like biomass, are now available (see [10] for a complete list). Rotary kilns with 5 or 6 suspension preheaters and precalciners are the most advanced technology available for clinker production and are usually adopted in the (semi-)dry processes[3].

Considering that CO_2 and the other greenhouse gas emissions are the undesirable but unavoidable outputs of the cement production process, these can be curbed only by reducing the ratio clinker to cement[4], increasing the utilization of alternative fuel and raw materials and improving technology energy efficiency. The application of these policies could have a positive impact on environment. This has also an economic effect for those companies operating in countries that price CO_2 through a market of emission permits. This is the case of the cement industries operating in Europe. Since 2005, the European Emission Trading Scheme (the EU-ETS) regulates CO_2 emissions generated by cement, energy, refining, iron, steel, pulp and paper plants. Introduced by Directive 2003/87/EC, the EU-ETS is the widest cap and trade system applied in the world. It imposes a CO_2 emission ceiling for all covered installations in the different countries and a parallel creation of an emission

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[1] These countries respectively produced 1,637 and 193 million tons of cement in 2009 (see Cembureau [4])

[2] According to Ponnsard and Walker [24] one ton of cement is typically composed for the 80% of clinker and for the remaining 20% of other materials. For more details see [10].

[3] The thermal energy required by this technology amounts to 3,100-4,200 MJ/ton clinker (see [10])

[4] Namely, the amount of clinker needed to produce one ton of cement.

allowance market. The Directive has regulated the two first phases of the EU-ETS: the so-called "learning by doing" phase started in 2005 and ended in 2007 and the second phase covering the years 2008-2012. Even though, during these two periods the installation have freely received a consistent number of CO_2 allowances (allocation through grandfathering), the EU-ETS has shown to be quite costly especially for energy intensive industries. This may have a negative effect on international competitiveness of these industries. There is a huge literature discussing these problems, but it goes beyond the scope of this paper.

Note that new Directive 2009/29/EC, that will regulate the third EU-ETS phase (2013-2020), tries to mitigate the problems of the first EU-ETS Directive by enlarging the number of sectors and greenhouse gases subject to regulation, imposing a full auctioning system for the energy sector and a progressive abandon of the grandfathering allowance allocation method for the other sectors. An open issue is the so-called "carbon leakage" effect that indicates an increase of CO_2 emissions in non EU-ETS countries versus a corresponding decrease of CO_2 emission in EU-ETS countries. In other words, a transfer of emissions that underlies a relocation of production activities is registered as a direct consequence of the lack of a worldwide environmental regulation. In many regions, such as of Japan, Canada, Switzerland and the USA (see Reinaud [26] for a complete review) emission regulation systems have been only announced, proposed or are applied on voluntary basis. However, one can notice a growing awareness about greenhouse gas emissions and, in general, about environmental issues in developing countries. China is the world's largest CO_2 emitter, but it has shown a determination to curb its greenhouse gas emissions by introducting of the China's national Climate Change Program[5] that aims at reducing greenhouse gas emissions by setting binding energy intensive reduction targets, stringent fuel efficiency standards and investments in more efficient technologies. The Chinese example has been followed by other developing countries like India[6], Brazil[7] and Turkey.

Considering the environmental and the economic roles assumed by CO_2 emissions we intend to measure the efficiency of cement production at worldwide level. In our analysis, we define efficiency as the ability of producing a certain good by saving energy and resources and/or reducing waste and emissions. In literature there exists several indicators measuring efficiency by comparing two or few production factors (see Tyteca for a complete overview [30]), but the one resulting from the application of the Data Envelopment Analysis (DEA) approach is the most comprehensive one. Specifically, DEA evaluates the efficiency of chosen Decision Making Units (DMUs), that can been plants, firms or even entire sectors, producing a homogeneous good. DEA model has the comparative advantage to simultaneously consider a multiplicity of inputs and both desirable (produced good) and undesirable (waste and pollutants) outputs that characterize a certain production process. In other words, it provides an immediate information on DMUs global efficiency (or inefficiency) status and, depending on the model adopted, gives information on which input or output the studied units have to intervene in order to improve their production efficiency.

To the best of our knowledge, few papers treat undesirable outputs of cement sector as a DEA model and in all of them only interstate analyzes have been developed (Bandyopadhyay [2], Mandal and Madheswaran [20] and Sadjadi and Atefeh [27]).

In this paper, we depart from this assumption and we compare prototypes of cement industries

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[5] See `http://www.ccchina.gov.cn/WebSite/CCChina/UpFile/File188.pdf`

[6] An Energy Conservation Act has been introduced in 2001. See `http://www.powermin.nic.in/acts_notification/pdf/ecact2001.pdf`

[7] The National Climate Change Plan entered in force in 2009. See `http://www.eoearth.org/article/Greenhouse_Gas_Control_Policies_in_Brazil`

operating around the world. In particular, we evaluate the efficiency level of twenty-one world countries in terms of cement and clinker production. This set of countries includes the world major producers (China, India, the USA, Japan and Turkey), almost all European producers in addition to Canada, Australia and Brazil. Taking CO_2 emissions as undesirable factor, we compare the results of a standard DEA model and a directional distance function approach. In order to evaluate the importance of emission regulation on efficiency we analyze these two classes of models with and without undesirable factors. The results show that the average efficiency measures obtained by the models including both desirable and undesirable factors significantly differ from those obtained omitting CO_2 emissions. When incorporating undesirable factors, the efficiency of both the whole cement production process and the clinker sub-process are explored. Finally, the models have been tested under the hypothesis of weak and strong disposability in order to evaluate the cost arising from environmental regulations.

The paper is organized as follows. Section 2 presents a literature review and illustrate the model that we adopt in our analysis. Sections 3 and 4 respectively illustrate the dataset and the simulation results. Final remarks are reported in Section 5.

2 Model specification

Data Envelopment Analysis (DEA) has been first proposed in the pioneering paper by Charnes, Cooper and Rhodes (CCR) [6]. It is a nonparametric method for estimating the efficiency of decision-making units (DMUs), such as firms or public sector agencies. In the classic DEA model, there are n DMUs to be evaluated. Each DMU consumes various inputs to produce different outputs. No production function needs to be specified.

In the classic DEA linear fractional program model (see [6]), the efficiency of the j^{th} DMU is defined by the ratio between the weighted sum of outputs and the weighted sum of inputs. In fact, since multiple inputs are used to produce multiple outputs then the individual inputs quantities and the individual outputs quantities need to be aggregated into a composite input and a composite output. The pioneer model (CCR) measures technical efficiency of a DMU which exhibits Constant Returns to Scale (CRS) everywhere on the production frontier. In an important extension of this approach, Banker, Charnes and Cooper [3] generalized the original DEA approach formulating a model (BCC) for exhibiting Variable Returns to Scale (VRS) at different points on the production frontier.

DEA evaluates the efficiency of each DMU through the better system of weights (or shadow prices) for the considered DMU, identifying the best one. Stating the benchmark DMU, DEA classifies the remaining DMUs from the most efficient to the less one. However, both desirable (good) and undesirable (bad) output and input factors may be present.

In this work we try to answer to the following questions: do undesirable factors modify the efficiency levels of cement industry? Is it reasonable to omit CO_2 emissions in evaluating the performances of the cement sector in different countries? In order to evaluate these sentences, the standard DEA formulation is compared with alternative formulations which include undesirable factors. Two different approaches can be followed: including undesirable factors as inputs or, according to the production process, considering undesirable factors as undesirable output.

When undesirable factors are taken into consideration, the choice between two alternative disposable technologies (improved technologies or reference technologies) has an important impact on DMUs efficiencies. Technology disposability can also be read in terms of strong and weak disposability of undesirable outputs. A production process is said to exhibit strong disposability of undesirable outputs (such as heavy metals, CO_2, etc.), if the undesirable outputs are freely disposable, i.e. they do not have limits. The case of weak disposability refers to situations where a reduction in waste or emissions forces a lower production of desirable outputs. In other words, in order to meet some emission limits (for instance because of regulatory constraints), a reduction of undesirable outputs may not be possible without assuming certain costs (see Zofío and Prieto, [34]).

For the sake of convenience, the list of common parameters used in the different models is provided below.

Parameters:

$x_{ij} \in \mathbb{R}_+$: i^{th} input quantity used by the j^{th} decision making unit
$i = 1, \dots, m, \quad j = 1, \dots, n$

$y^g_{rj} \in \mathbb{R}_+$: r^{th} "good" output quantity produced by the j^{th} decision making unit
$r = 1, \dots, q, \quad j = 1, \dots, n$

$y^b_{kj} \in \mathbb{R}_+$: k^{th} "bad" output quantity produced by the j^{th} decision making unit
$k = 1, \dots, l, \quad j = 1, \dots, n$

According to the literature, two different approaches can be used to model undesirable factors: a first group of DEA models treats them as inputs, while a second one considers them as undesirable outputs. In the light of this distinction, we now present the four alternative DEA models that we will compare in order to measure the impact of CO_2 emissions on the efficiency of the cement industry.

2.1 A first model comparison: standard BCC DEA model and undesirable factors treated as inputs

The first DEA model we consider is the standard BCC model following the lines of Banker et al. [3]. The original formulation of this model does not comply the presence of undesirable output. According to this model, in the input oriented version, DMU efficiency is defined as the ability to contract the amount of inputs without reducing the corresponding output volumes. The mathematical formulation of the model $M1$ is as follows:

$$(M1)$$

$$\min_{\theta,\lambda} \ \theta \tag{1}$$

$$s.t. \quad \sum_{j=1}^{n} \lambda_j y^g_{rj} \geq y^g_{rj_0} \quad r = 1, \dots, q \tag{2}$$

$$\sum_{j=1}^{n} \lambda_j x_{ij} \leq \theta x_{ij_0} \quad i = 1, \dots, m \tag{3}$$

$$\sum_{j=1}^{n} \lambda_j = 1 \tag{4}$$

$$\lambda_j \geq 0 \quad j = 1, \dots, n$$

where variables θ and λ_j are respectively defined as follows:

$\theta \in \mathbb{R}_+$: radial efficiency measure

$\lambda_j \in \mathbb{R}_+$: intensity factor associated to each DMU $j = 1, \ldots, n$

A first approach, where both desirable and undesirable factors are considered, suggests to include undesirable outputs as desirable inputs in the production process (see [18]). Its starting point is that efficient DMUs wish to minimize desirable inputs and undesirable outputs while maximizing desirable outputs and undesirable inputs. The mathematical formulation of the model, in case of strong disposability and input oriented DEA, is as follows:

$$(M2)$$

$$\min_{\theta,\lambda} \quad \theta \tag{5}$$

$$s.t. \quad \sum_{j=1}^{n} \lambda_j y_{rj}^g \geq y_{rj_0}^g \quad r = 1, \ldots, q \tag{6}$$

$$\sum_{j=1}^{n} \lambda_j y_{kj}^b \leq \theta y_{kj_0}^b \quad k = 1, \ldots, l \tag{7}$$

$$\sum_{j=1}^{n} \lambda_j x_{ij} \leq \theta x_{ij_0} \quad i = 1, \ldots, m \tag{8}$$

$$\sum_{j=1}^{n} \lambda_j = 1 \tag{9}$$

$$\lambda_j \geq 0 \quad j = 1, \ldots, n$$

Considering our analysis where CO_2 emissions are the undesirable factor of cement/clinker production, the comparison between models $M1$ and $M2$ provides information on the effects of considering CO_2 emissions as an input of the production process. Model $M2$, in facts, attempts to proportionately contract both desirable inputs and the CO_2 undesirable output. The differences in efficiency between models $M1$ and $M2$ can be interpreted as a greater or lower efficiency in absence of environmental regulation.

Since the prominent interest of national authorities is to curb CO_2 emissions by environmental regulation, constraints (7) in model $M2$ can be slightly modified in order to assume weak disposability of undesirable input. In this light the efficiency measure can evaluate the ability to contract all inputs of the production process without increasing the amount of CO_2 emitted.

Under weak disposability assumption model $M2$ is then modified as follows:

$(M2weak)$

$$\min_{\theta,\lambda} \quad \theta \tag{10}$$

$$s.t. \quad \sum_{j=1}^{n} \lambda_j y_{rj}^g \geq y_{rj_0}^g \quad r = 1, \dots, q \tag{11}$$

$$\sum_{j=1}^{n} \lambda_j y_{kj}^b = \theta y_{kj_0}^b \quad k = 1, \dots, l \tag{12}$$

$$\sum_{j=1}^{n} \lambda_j x_{ij} \leq \theta x_{ij_0} \quad i = 1, \dots, m \tag{13}$$

$$\sum_{j=1}^{n} \lambda_j = 1 \tag{14}$$

$$\lambda_j \geq 0 \quad j = 1, \dots, n$$

The comparison between models $M1$ and $M2weak$ can highlight the importance of considering CO_2 emissions in efficiency assessment in presence of environmental regulations which curb CO_2 emissions. The analysis of weak and strong disposability assumptions gives information on the use of alternative fuels and raw materials in order to reduce CO_2 levels maintaining the same efficiency levels and output quantities. For an exhaustive discussion on strong and weak disposability in these models see Liu et al. [17].

2.2 A second model comparison: the directional distance function approach and undesirable factors treated as output

The directional output distance function, in its original formulations by Färe et al. [13], is an alternative approach to evaluate efficiency. This approach evaluates efficiency as the ability of simultaneously expanding desirable outputs and contracting inputs.

Let T be the technology set, such that:

$$T = [(x, y^g) : x \text{ can produce } y^g] \tag{15}$$

the directional technology distance function generalizes both input and output Shephard's distance functions, providing a complete representation of the production technology.

Let $d = (-d^x, d^g)$ be a direction vector, the function is formally defined as:

$$\vec{D}_T(x, y^g; d) = \sup\,[\delta : (x - \delta d^x, y^g + \delta d^g) \in T] \tag{16}$$

Expression (16) seeks for the maximum attainable expansion of desirable outputs in the d^g direction and the largest feasible contraction of inputs in d^x directions. Under the assumptions made on the reference technology, the directional technology distance function of expression (16) can be computed for firm j_0 by solving the following linear programming problem:

$$
\begin{aligned}
&(M3)\\
&\max_{\delta,\lambda} \quad \delta\\
&s.t. \quad \sum_{j=1}^{n} \lambda_j y^g_{rj} - \delta d^g_{rj_0} \geq y^g_{rj_0} \quad r = 1, \ldots, q && (17)\\
&\qquad \sum_{j=1}^{n} \lambda_j x_{ij} + \delta d^x_{ij_0} \leq x_{ij_0} \quad i = 1, \ldots, m && (18)\\
&\qquad \sum_{j=1}^{n} \lambda_j = 1\\
&\qquad \lambda_j \geq 0 \quad j = 1, \ldots, n
\end{aligned}
$$

Notice that in the directional distance function model, efficiency is reached when $\delta = 0$, corresponding to the case of $\theta = 1$ in the standard DEA formulations.

The choice of a direction vector $d = (-x, y^g)$ permits to evaluate a global technology by reducing inputs and simultaneously expanding desirable outputs. A different direction vector can be used in order to restrict the analysis on output factors, by considering, for instance, a direction vector $d = (0, y^g)$.

Extensions of this methodology in presence of undesirable outputs (see for all [11, 12, 23]) leads to a measure of technical efficiency from the potential for increasing outputs while reducing inputs and undesirable outputs simultaneously.

The technology set, including undesirable factors, can be modified as follows:

$$T = \Big[(x, y^g, y^b) : x \text{ can produce } (y^g, y^b)\Big] \tag{19}$$

Let $\mathscr{P}(x)$ be the set of all the feasible output vectors (y^g, y^b) for a given input vector x:

$$\mathscr{P}(x) = \Big[(y^g, y^b) : (x, y^g, y^b) \in T\Big] \tag{20}$$

the directional technology distance function considering also undesirable factors is formally defined as:

$$\vec{D}_T(x, y^g, y^b; d) = \sup\Big[\delta : (y^g + \delta d^g, y^b - \delta d^b) \in \mathscr{P}(x - \delta d^x)\Big] \tag{21}$$

where $d = (-d^x, d^g, -d^b)$. Expression (21) seeks for the maximum attainable expansion of desirable outputs in the d^g direction and the largest feasible contraction of undesirable outputs and inputs in d^b and d^x directions. The directional technology distance function of expression (21), once defined the technology of reference, is the solution of the following optimization model (taking j_0 as reference unit):

$$
\begin{array}{lll}
(M4) & & \\
\max\limits_{\delta,\lambda} & \delta & \\
s.t. & \sum\limits_{j=1}^{n} \lambda_j y^g_{rj} - \delta d^g_{rjo} \geq y^g_{rjo} \quad r = 1, \ldots, q & (22) \\
& \sum\limits_{j=1}^{n} \lambda_j y^b_{kj} + \delta d^b_{kjo} \leq y^b_{kjo} \quad k = 1, \ldots, l & (23) \\
& \sum\limits_{j=1}^{n} \lambda_j x_{ij} + \delta d^x_{ijo} \leq x_{ijo} \quad i = 1, \ldots, m & (24) \\
& \sum\limits_{j=1}^{n} \lambda_j = 1 & \\
& \lambda_j \geq 0 \quad j = 1, \ldots, n &
\end{array}
$$

Similarly to model $M3$, the choice of a direction vector $d = (0, y^g, -y^b)$ focus the attention on expansion of desirable factors and contraction of undesirable ones without increasing the inputs (see Mandal and Madheswaran [20] for a such approach).

Let us finally recall that this model can be also considered under the assumption of weak disposability by assuming that constraints (23) hold with equality. The corresponding weak disposability formulation is as follows:

$$
\begin{array}{lll}
(M4weak) & & \\
\max\limits_{\delta,\lambda} & \delta & \\
s.t. & \sum\limits_{j=1}^{n} \lambda_j y^g_{rj} - \delta d^g_{rjo} \geq y^g_{rjo} \quad r = 1, \ldots, q & (25) \\
& \sum\limits_{j=1}^{n} \lambda_j y^b_{kj} + \delta d^b_{kjo} = y^b_{kjo} \quad k = 1, \ldots, l & (26) \\
& \sum\limits_{j=1}^{n} \lambda_j x_{ij} + \delta d^x_{ijo} \leq x_{ijo} \quad i = 1, \ldots, m & (27) \\
& \sum\limits_{j=1}^{n} \lambda_j = 1 & \\
& \lambda_j \geq 0 \quad j = 1, \ldots, n &
\end{array}
$$

2.3 Construction of the production frontier

In the DEA literature, three types of frontiers have been proposed to evaluate efficiency in a panel-data framework. The first one is the standard Contemporaneous Frontier, where the frontier in each year is formed by only the observations of the year under consideration. The second type of frontier is the Intertemporal Frontier and it is based on observations from all the considered periods at a time. The third one is the Sequential Frontier, where each observation for a given year is compared to all other observations in the same year and to observations in the previous years (see Tulkens and Eeckaut [32] for a detailed discussion about different DEA frontiers). This last methodology is based on the assumption that the production possibility set can expand each year and no technological regress is admitted. For the aim of this work, the Sequential Frontier seems to be the most suitable for the analysis of the world cement sector in the years 2005-2008. In these years, in facts, the world cement industry has faced a rapid expansion and technological improvement (especially in developing countries). For classical DEA applications with sequential frontier, the production possibility set is defined as

$$S = \left\{ (x,y) : x \geq \sum_{j=1}^{n} \sum_{t=1}^{T} \lambda_j x_j^t; \quad y \leq \sum_{j=1}^{n} \sum_{t=1}^{T} \lambda_j y_j^t; \quad \sum_{j=1}^{n} \lambda_j = 1 \right\}$$

where there are n units observed and t corresponds to the time period at which the DMU is being evaluated[8].

3 Database description

We have built up a database concerning the cement production of twenty-one world countries. This dataset includes both European (EU) and non-European (non-EU) countries in order to take into account different economic, geographic and emission regulation aspects. Among the European States we consider: Austria, Belgium, Czech Republic, Denmark, Estonia, France, Germany, Italy, Norway, Poland, Spain, Switzerland and UK. These countries globally produce more than the 80% of the total EU cement production. We also account for Australia, Brazil, Canada, China, India, Japan, U.S.A. and Turkey.

For the purpose of our analysis, the choice of input and output factors of DEA models has been done taking into account the cement and clinker production processes. In this light, for all the models presented in Section 2 two different instances have been considered: in the first instance (CEM) we focus on the entire cement production process, in the second one (CLK) we limit our attention on clinker. For this reason, in CEM we take clinker, installed cement capacity, energy, labour and raw materials as inputs. Desirable output is represented by cement production while CO_2 emissions are the undesirable by-product. More specifically, clinker includes both imports and local production, capital corresponds to installed cement capacity (a similar approach can be found in Fare et al. [14], Tyteca [31]), energy results from the sum of electricity and thermal energy, labour is the number of employees and finally, raw materials is defined as the sum of slug, limestone and all those additives needed in cement production.

Desirable output is Portland cement production. The undesirable by-product is measured by the value of carbon dioxide emissions (CO_2) mainly resulting from the clinker production process without considering those related to raw material, fuels and clinker transportation. CO_2 can be interpreted as input or undesirable output according to the different DEA approaches.

Data sources for EU countries are the European association of cement industries (Cembureau), the national cement association of the different countries (see Cembureau website for the link to

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[8] The constraints for the DEA models presented in Section 2 are revised accordingly.

members' national associations and Appendix A), OECD (especially for labour data), Eurostat and ComTrade (for clinker import/export data), European Pollutant Emission Registry (EPER for CO_2 emission data). National cement associations also provided data for non-EU countries (see the detailed list of the references in Appendix A).

Missing data on emission factors have been estimated according to Intergovernmental Panel on Climate Change (IPCC)[9]. Carbon dioxide is released during the production of clinker in which calcium carbonate ($CaCO_3$) is heated in a rotary kiln to induce a series of complex chemical reactions. Specifically, CO_2 is released as a by-product during calcination, which occurs in the upper, cooler end of the kiln, or a precalciner, at temperatures of 600-900C, and results in the conversion of carbonates to oxides. The simplified stoichiometric relationship is as follows:

$$CaCO_3 + heat \rightarrow CaO + CO_2 \tag{28}$$

At higher temperatures in the lower end of the kiln, the lime (CaO) reacts with silica, aluminum and iron containing materials to produce minerals in the clinker. The clinker is then removed from the kiln to cool, ground to a fine powder, and mixed with a small fraction (about 5%) of gypsum to create the most common form of cement known as Portland cement.

The formula to calculate CO_2 emission has been defined according to the following steps:

1. Data on clinker production (in tonnes) have been collected. In case of missing data the clinker production has been estimated as a fixed proportion on cement production (estimated coefficient varying between 75% and 95% according to the cement blending).

2. Ton of Raw Material (T) per Ton of Clinker (*RM/clinker ratio*) have been estimated in the case of data missing with a fixed coefficient of 1.54 according to IPCC guidelines.

3. The $CaCO_3$ Equivalent to Raw Material Ratio (%) is fixed to a 78.5%.

4. The CO_2 to $CaCO_3$ Stoichiometric Ratio is fixed equal to 0.44.

The total CO_2 emissions expressed in tonnes (T) can be estimated as follows:

$$CO_2 = clinker(T) \cdot (RM/clinker\ ratio) \cdot CaCO_3\% \cdot 0.44 \tag{29}$$

In Table 1, we report means and standard deviations of the input and output parameters used in the first instance simulation for the considered 2005-2008 period and the ratios between clinker, energy, CO_2 and cement production. Note that the high standard deviation values depend on the inclusion of China in the dataset. Cement industry in China, in facts, accounts for more than 40% of world cement production. The time-varying analysis of mean values in Table 1 shows that the worldwide cement production has grown since 2005 with a peak value in 2007 and a stable figure in 2008. This growth is mainly ascribed to Turkey and non-OECD countries that are developing their economies with relatively lenient environmental limits. Moreover the clinker to cement ratio shows a progressive reduction (from 0.79 in 2005 drops to 0.72 in 2008) thanks to the use of alternative raw material in the cement production process and the increasing production of blended cement (at least in some developing countries) which requires a lower proportion of clinker. A similar behavior can

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[9] see http://www.ghgprotocol.org/calculation-tools/cement-sector for the clinker based tool suitable when the amount of clinker consumed is known. We also recall that only direct emissions have been considered in this work.

	2005		2006		2007		2008	
Variable	**Mean**	**Std Dev**	**Mean**	**Std Dev**	**Mean**	**Std Dev**	**Mean**	**Std Dev**
Capacity (Ml t)	139.74	320.05	170.75	437.79	169.94	430.95	169.52	424.16
Energy (TWh)	89.17	273.83	98.96	312.62	99.33	310.03	95.30	294.43
Labour (x1000)	77.64	297.01	89.10	347.41	97.02	381.06	99.73	392.24
Clinker (Ml t)	63.42	176.74	70.67	204.15	74.67	217.90	71.21	205.11
Import clinker	0.70	1.71	1.03	2.12	0.98	2.34	0.62	1.21
Raw materials (Ml t)	114.12	324.43	128.88	379.91	138.68	417.01	141.88	429.68
Cement (Ml t)	79.68	222.05	89.91	260.04	96.54	285.40	97.92	294.14
CO2 (Ml t)	68.13	205.65	76.32	237.12	79.88	251.35	80.23	254.60
Ratio	**Ratio**		**Ratio**		**Ratio**		**Ratio**	
Clinker/Cement	0.7959		0.7859		0.7735		0.7272	
Energy/Cement	1.1191		1.1006		1.0289		0.9733	
CO2/Cement	0.8550		0.8488		0.8275		0.8194	

Table 1: Cross Sectional Mean and Standard Deviation of CEM instance variables and relevant ratios.

be found in energy consumption where the increasing use of alternative fuels, like waste or biomass justifies the corresponding decreasing of the energy/cement ratio. The combination of these two effects leads to a reduction of CO_2 emission over time.

The second set of computational tests (CLK) gives information on efficiency of the clinker production process which is the main responsible of CO_2 emissions. In order to evaluate the clinker process efficiency in the twenty-one countries, three input factors have been taken into account, namely energy and raw materials consumed in the clinker production and labour. Clinker production is the desirable output while CO_2 emissions are the undesirable one.

Since the aim of this work is to evaluate the efficiency of different countries, all input and output are divided by the total number of plants for each country in order to determine the efficiency of a representative plant within each country (a similar approach can be found in Mandal [19], Mandal and Madheswaran [20], Mukherjee [21]).

4 Empirical Results

Both the DEA model and the directional distance function described in Section 2 have been implemented in MatLab 2010a in order to evaluate the efficiency of the cement sector in presence or absence of undesirable factors.

The methodology used to evaluate these efficiency measures is based on a sequential frontier approach. In this way we avoid the possibility of "technical regress", since sequential frontier assumes all current and past observations as feasible. Starting then with a reference sample of twenty-one observations for the year 2005, we successively accumulate the observations of one more year to create the frontier of each subsequent period. To avoid imbalances caused by different magnitudes, input and output parameters are normalized with respect to their average values (see Table 1).

Both CEM and CLK instances have been analyzed with and without undesirable factors. As a consequence, the relevance of including CO_2 emissions in the study of efficiency in countries involved in environmental regulations can be tested.

Tables 2 and 3 and 4 and 5 respectively report the results of computational test from models $M1$, $M2$ and $M2weak$ applied to both CEM and CLK instances. We recall that model $M1$ values the efficiency through input reductions and do not include undesirable by-products. The study of efficiency using $M2$ and $M2weak$ models gives information on the efficiency taking into account both input and CO_2 reductions in absence or presence of environmental regulations.

Tables 6, 7, 8 and 9 list the results obtained from models $M3$, $M4$ and $M4weak$ based on the directional distance approach applied to both CEM and CLK instances. Model $M3$ evaluates the expansion of desirable output without considering undesirable factors; models $M4$ and $M4weak$ simultaneously measure the undesirable output contraction and desirable output expansion in absence or presence of environmental regulations respectively.

4.1 Efficiency evaluation: standard BCC DEA model and undesirable factors treated as inputs

In this paragraph the results of instances CEM and CLK investigated with DEA models of Section 2.1 are presented. Tables 2 and 3 are related to CEM instance that considers the whole cement production process. Table 2 shows the cement production efficiency values based on the classical DEA model $M1$ which considers only desirable outputs. The average world efficiency is equal to 0.93775, this implies that it would be possible to reduce input factors by a maximum amount of 6.23% and still produce the given level of output. However, the efficiency level varies among the considered countries. While Brazil and China remain efficient during the whole period under analysis, Denmark, India, and Spain reach an efficiency level close to 100%. The worst performing countries are Estonia, Turkey, U.S.A. Norway and United Kingdom. As concerning the country average, a progressive decline in efficiency can be observed: the average level of efficiency 0.96 in 2005 drops to 0.9273 in 2008 (3.27%).

Table 3 presents the results of models $M2$ and $M2weak$ that include both desirable and undesirable outputs. In particular, model $M2$ assumes that no environmental regulation is applied while model $M2weak$ assumes that all the 21 countries are subject to any environmental normative. While comparing the efficiency scores provided by model $M1$ (Table 2) and model $M2weak$ (Table 2), it can be seen that the average efficiency measure obtained by model $M2weak$ is substantially higher than the one obtained from model $M1$. In order to verify whether omitting undesirable output can affect efficiency estimations, the Wilcoxon Signed Rank Test has been conducted. The null hypothesis is that the efficiency scores obtained from the two models belong to the same population of relative frequency distribution, whereas alternative hypothesis is that the mean efficiency value obtained with model $M1$ significantly differs from the one obtained with $M2weak$ model. The value of Wilcoxon statistics is 3.82 and the value of two tailed "p" statistic is lower than 0.0001. Then, the null hypothesis can be rejected at 1% level, implying that omitting CO_2 emissions (undesirable output) results in biased efficiency estimates.

In Table 2 efficiency scores of models $M2$ and $M2weak$ are directly compared. It is worth noticing that mean efficiency scores under the weak disposability assumption are strictly higher than the ones related to the strong disposability assumption and this difference increases over years. Four countries show efficiency scores equal to one, namely China, Brazil, Estonia and India. Switzerland, Japan and Denmark are very close to 100% efficiency. This implies that average efficiency in presence of environmental regulation is higher than that obtained in absence of it. In other words without regulation an additional contraction of 2% of input factors (good input and pollutant) can be reached

Table 2: CEM instance: efficiency scores based on Standard BCC DEA model ($M1$)

Country	**2005**	**2006**	**2007**	**2008**	**Annual average**[b]
Australia	1	0.82653	0.83476	0.84843	0.87743
Austria	1	0.93766	0.96267	0.97907	0.96985
Belgium	1	1	0.96747	0.97095	0.98461
Brazil	1	1	1	1	1
Canada	0.99654	1	0.99125	0.94537	0.98329
China	1	1	1	1	1
Czech Republic	1	0.91053	0.92137	0.9233	0.9388
Denmark	1	1	1	0.99336	0.99834
Estonia	0.85171	0.85815	0.76254	0.65691	0.78233
France	0.91878	0.92693	0.90822	0.92649	0.92011
Germany	0.94205	0.97557	0.91795	0.96376	0.94983
India	1	1	1	0.99244	0.99811
Italy	1	1	0.99326	0.96179	0.98876
Japan	1	0.99769	1	0.98759	0.99632
Norway	0.87686	0.84397	0.86662	0.88002	0.86687
Poland	0.97027	0.80569	0.84129	0.99987	0.90428
Spain	1	1	1	0.97643	0.99411
Switzerland	0.94282	0.93559	0.93518	0.93602	0.9374
Turkey	0.87014	0.88991	0.86754	0.85285	0.87011
U.S.A.	0.93147	0.89994	0.89371	0.85589	0.89525
United Kingdom	0.86053	0.83083	0.83243	0.82379	0.8369
Country average[a]	0.96006	0.93519	0.92839	0.92735	0.93775

[a] Country average is the average efficiency of the 21 countries for a given year.

[b] Annual average is the average efficiency for a given country over 4 years.

without reducing the corresponding good output. The Wilcoxon Signed Rank Test has been used to compare the efficiency mean results under these two hypothesis. The value of Wilcoxon statistic is 3.18 with a two tailed p-value equal to 0.0016. The hypothesis of no difference among efficiency scores under strong and weak disposability assumption can be rejected at 1% confidence level, namely the assumption of weak or strong disposability significantly influences the efficiency measure. In this case environmental regulations have a double effect: to curb CO_2 emissions and to improve the good input contraction by the use of alternative fuels and raw materials.

Table 3: CEM instance: efficiency scores based on models $M2$ and $M2weak$

Country	2005		2006		2007		2008		Annual average	
	Strong	Weak	Strong	Weak	Strong	Weak	Strong	Weak	Strong	Weak
Australia	1	1	0.8271	0.8271	0.83493	0.83493	0.85088	0.85088	0.87823	0.87823
Austria	1	1	0.93766	0.96493	0.96267	1	0.97907	1	0.96985	0.99123
Belgium	1	1	1	1	0.96747	0.98484	0.97881	0.97881	0.98657	0.99091
Brazil	1	1	1	1	1	1	1	1	1	1
Canada	0.99654	1	1	1	0.99125	0.99784	0.94537	0.98463	0.98329	0.99562
China	1	1	1	1	1	1	1	1	1	1
Czech Republic	1	1	0.91053	0.91245	0.92137	0.94315	0.9233	0.93387	0.9388	0.94737
Denmark	1	1	1	1	1	1	0.99402	0.99402	0.9985	0.9985
Estonia	0.85171	1	0.85815	1	0.76254	1	0.65691	1	0.78233	1
France	0.92246	0.92246	0.9314	0.9314	0.91293	0.91293	0.93162	0.93162	0.9246	0.9246
Germany	0.94556	0.94556	0.98204	0.98204	0.92096	0.92096	0.97159	0.97159	0.95504	0.95504
India	1	1	1	1	1	1	0.99244	1	0.99811	1
Italy	1	1	1	1	0.99326	1	0.96179	0.96179	0.98876	0.99045
Japan	1	1	0.99769	1	1	1	0.98759	0.98845	0.99632	0.99711
Norway	0.87686	0.89016	0.84397	0.85725	0.86662	0.87923	0.88002	0.88543	0.86687	0.87802
Poland	0.97027	0.97845	0.80569	0.85011	0.84129	0.86738	1	1	0.90431	0.92398
Spain	1	1	1	1	1	1	0.97979	0.97979	0.99495	0.99495
Switzerland	1	1	1	1	0.99965	0.99965	1	1	0.99991	0.99991
Turkey	0.87014	0.93516	0.88991	0.9201	0.86754	0.86936	0.85285	0.85441	0.87011	0.89476
U.S.A.	0.93147	1	0.89994	0.9695	0.89371	0.96737	0.85589	0.94683	0.89525	0.97093
United Kingdom	0.86053	0.87859	0.83083	0.84594	0.83243	0.85625	0.82379	0.87551	0.8369	0.86407
Country average	0.96312	0.97859	0.93881	0.95528	0.93184	0.954	0.9317	0.95893	0.94137	0.9617
Improvement	0.01547		0.01647		0.02216		0.02723		0.02033	

Tables 4 and 5 present the results concerning CLK instance. Taking into account that clinker production process is the main responsible of CO_2 direct emissions, CLK instance is focused on this production sub-process. We recall that in these computational tests three inputs are taken into account (raw materials and energy related to the clinker production process, labour) and one desirable output, namely clinker production. As in the previous case, we analyze whether the efficiency scores can vary in presence or absence of undesirable factor. The study of clinker production efficiency provides informations on the ability of substituting classical raw materials and fuels with alternative ones that produce less emissions and it avoids imbalances in efficiency scores due to the different composition of Portland Cement. The varieties of Portland Cement, in facts, can contain different proportions of clinker and raw materials. Blended cements are the cement varieties with the lower clinker percentage and they are mainly produced in developing countries. A third aspect which has to be taken into account is the possibility of importing clinker. Countries involved in environmental regulations can decide to import clinker from unregulated countries in order to curb CO_2 emissions and produce higher cement quantities without incurring in additional costs (acquisition of additional emission permits or emission penalties).

Tables 4 collects the results of $M1$ applied to CLK instance. The average world efficiency is equal to 0.9225; this implies that it would be possible to reduce input factors by a maximum amount of 7.75% and still produce the given level of output. With respect to the corresponding results of Table 2, clinker production process seems to be less efficient than the cement one. Let us, however, recall that a direct comparison can not be stated since the DEA models provide a relative efficiency measure that depends on the peer units of the considered instance.

It can be easily seen that the efficiency level varies among the considered countries. The benchmark unit is Austria during the whole period under analysis and China, Belgium and Switzerland are very close to efficiency. The worst performing countries are Brazil, Turkey, Australia, and Italy. As concerning the country average, a progressive decline in efficiency can be observed: the average level of efficiency 0.94 in 2005 drops to 0.89 in 2008. It can be also noticed that countries involved in environmental regulation seem to perform better in clinker production process. This can be a positive effect of the regulation which force these countries to adopt efficient technologies and to increase the use of alternative materials and fuels.

These results are confirmed if we refer to efficiency scores collected in Table 5. Model $M2weak$ shows that Austria, China, India and Switzerland are efficient followed by Belgium, Canada, Japan and the U.S.A. Let us notice that Brazil when considering only the clinker production has a significant drop in efficiency. This can be explained by taking into account that Brazil mainly produces blended cement that requires a lower proportion of clinker and that the use of alternative fuels in this country is irrelevant. As concerning the country average efficiency among years, starting from the level of 0.95375 in 2005 it decreases to the level of 0.90733 in 2008. This trend slightly increases in 2007 and significantly decreases in 2008. In terms of environmental regulation let us recall that the EU-ETS normative in Europe faces a new phase in 2008 with more restrictive constraints on CO_2 emissions. The Statistical Wilcoxon Signed Rank Test has been conducted also for the CLK instance by firstly comparing the efficiency scores obtained with model $M1$ and model $M2weak$. In this case we test the null hypothesis of equal mean efficiency scores between the two models with respect to the alternative hypothesis of different efficiency scores. The value of Wilcoxon statistics is 3.92 and the value of two tailed "p" statistic is lower than 0.00001. Then, the null hypothesis can be rejected at 1% level, implying that omitting CO_2 emissions (undesirable output) results in biased efficiency estimates. Table 5 shows the comparison between efficiency scores in presence or absence of environmental

Table 4: CLK instance: efficiency scores based on Standard DEA model without CO_2 emissions

Country	**2005**	**2006**	**2007**	**2008**	**Annual average**
Australia	0.81311	0.81521	0.80488	0.78313	0.80408
Austria	1	1	1	1	1
Belgium	1	1	1	0.97642	0.99411
Brazil	0.77828	0.7646	0.78051	0.76188	0.77132
Canada	1	1	0.99575	0.94323	0.98475
China	1	1	0.99973	1	0.99993
Czech Republic	1	0.87418	0.93571	0.93979	0.93742
Denmark	1	0.98809	1	0.75093	0.93476
Estonia	0.91725	0.85088	0.8959	0.84416	0.87705
France	0.88141	0.85399	0.85436	0.84112	0.85772
Germany	0.91564	0.86108	0.89887	0.85143	0.88175
India	0.99856	0.94732	0.95253	0.9368	0.9588
Italy	0.82899	0.82412	0.82544	0.8172	0.82394
Japan	1	1	0.9536	0.94823	0.97546
Norway	1	0.93335	0.94148	0.94286	0.95442
Poland	0.87271	0.95857	0.9416	0.83787	0.90269
Spain	0.97513	0.96948	0.95831	0.90201	0.95123
Switzerland	1	0.979	1	0.98954	0.99214
Turkey	0.86896	0.8243	0.8297	0.85999	0.84574
U.S.A.	1	1	1	0.93394	0.98348
United Kingdom	1	0.96542	0.96309	0.84298	0.94287
Country average	0.94524	0.92427	0.93007	0.89064	0.92255

regulation in the CLK instance. As in the previous case The Statistical Wilcoxon Signed Rank Test has been conducted in order to test the differences in efficiency values under the strong or weak disposability assumption. The value of Wilcoxon statistics is 3.41 and the value of two tailed "p" statistic is lower than 0.0008. By considering strong and weak disposability assumptions, the main differences in efficiency values are related to India, which differs of an amount of 5% between the two models and Estonia that loses 10% of efficiency in the case of no environmental regulation. The input average contraction, including the undesirable CO_2 emissions, in the case of absence of regulation can be 1.1% greater than in the case of weak disposability assumption. This difference is substantially constant among the different years.

Table 5: CLK instance: efficiency scores based on Models $M2$ and $M2weak$

Country	2005		2006		2007		2008		**Annual average**	
	Strong	**Weak**	**Strong**	**Weak**	**Strong**	**Weak**	**Strong**	**Weak**	**Strong**	**Weak**
Australia	0.81311	0.83168	0.81521	0.81798	0.80488	0.80677	0.78313	0.78403	0.80408	0.81011
Austria	1	1	1	1	1	1	1	1	1	1
Belgium	1	1	1	1	1	1	0.99545	0.99545	0.99886	0.99886
Brazil	0.77828	0.7821	0.77211	0.77211	0.78751	0.78751	0.77002	0.77002	0.77698	0.77794
Canada	1	1	1	1	0.99698	0.99698	0.94633	0.94633	0.98583	0.98583
China	1	1	1	1	0.99973	1	1	1	0.99993	1
Czech Republic	1	1	0.8763	0.8763	0.93571	0.97303	0.93979	0.95985	0.93795	0.9523
Denmark	1	1	0.98809	1	1	1	0.75119	0.75119	0.93482	0.9378
Estonia	0.91725	1	0.85088	0.98369	0.8959	1	0.84416	0.92172	0.87705	0.97635
France	0.88141	0.89612	0.85399	0.85451	0.85436	0.85472	0.84607	0.84607	0.85896	0.86285
Germany	0.91564	0.93349	0.8663	0.8663	0.90257	0.90257	0.85877	0.85877	0.88582	0.89028
India	0.99856	1	0.94732	1	0.95253	1	0.9368	1	0.9588	1
Italy	0.82899	0.83407	0.82692	0.82692	0.82544	0.82667	0.82294	0.82294	0.82607	0.82765
Japan	1	1	1	1	0.97391	0.97391	0.96663	0.96663	0.98513	0.98513
Norway	1	1	0.93335	0.9443	0.94148	0.94215	0.94286	0.95347	0.95442	0.95998
Poland	0.87271	0.87799	0.95857	0.97648	0.9416	0.95085	0.84935	0.84935	0.90556	0.91367
Spain	0.97513	1	0.96948	0.99924	0.95831	0.97204	0.90201	0.90251	0.95123	0.96845
Switzerland	1	1	1	1	1	1	1	1	1	1
Turkey	0.86896	0.87326	0.82513	0.82513	0.84615	0.84615	0.88012	0.88012	0.85509	0.85616
U.S.A.	1	1	1	1	1	1	0.93465	0.93465	0.98366	0.98366
United Kingdom	1	1	0.96542	0.98067	0.96309	0.98235	0.84298	0.91074	0.94287	0.96844
Country average	0.94524	0.95375	0.92615	0.93922	0.93239	0.9436	0.89587	0.90733	0.92491	0.93597
Improvement	0.00851		0.01307		0.01122		0.01146		0.01106	

4.2 Efficiency evaluation: the directional distance function approach and undesirable factors treated as output

The results of models *M2* and *M2weak* presented in Section 4.1 are based on the assumption that undesirable factors (CO_2 emissions) are treated as an input of the production process and the efficiency measures evaluate the reduction of CO_2 emissions without changing the desirable output levels (cement production in CEM instance and clinker production in CLK instance). In this Section the computational results concerning the directional distance function both in presence and in absence of desirable factors are shown. Let us recall that in the case of Directional distance function the maximum efficiency level is reached when the score is equal to zero.

Table 6 and 8 lists the results of model *M3* that measures efficiency as the ability to expand desirable output maintaining fixed the input proportions referring to CEM instance and CLK instance, respectively. Directional distance function approach including undesirable factors (models *M4* and *M4weak*), whose results are presented in Tables 7 and 9 of this section, provides an alternative efficiency measure. It allows to measure the potential reduction of undesirable emission output and the potential expansion of desirable output. We consider both weak and strong disposability assumptions. Strong disposability implies that good outputs can be arbitrary expanded, while the weak disposability assumption limits their expansion according to existing regulation (that could imply an emission control). The difference between efficiency levels under weak and strong disposability in the directional distance approach can be interpreted as the cost of regulation with respect to the emission factors (see [20]) that we denote as "Normative Price" in Tables 7 and 9.

Let us focus on CEM instance whose results are presented in Tables 6 and 7. Table 6 shows the efficiency results without considering undesirable output. The average efficiency is 0.07868, meaning that cement production can be further expanded by 7.87% with the same input levels. In 2008 the maximum expansion level, that coincides with the minimum average efficiency, is reached as equal to 9.23%. The inefficiency slightly decreases in 2007 when the world cement demand achieved its maximum level over the period studied. It is reasonable to suppose that all countries have used all their available plants (efficient and non efficient) at full capacity in order to fulfill high demand levels.

The most efficient countries, according to this model, are Brazil and China, while Denmark, India, Japan and Spain have efficiency scores very close to zero. With respect to the same instance evaluated with DEA model (see Table 2 in the previous section), the most efficient countries are the same, while some differences can be accounted for countries whose efficiency is close to the peer units. Imbalances in efficiency scores can be found among years, efficient countries like Denmark, Spain, Belgium and Italy lose their efficiency in 2008.

In order to analyze more in details the reasons of this drop in efficiency, in Table 7 we compare the results of the directional distance function approach including undesirable output in the case of weak and strong disposability. We want to test if the second phase of EU-ETS normative, that imposes, starting from 2008, more restrictive limits on CO_2 emissions, can highlight the cause of the lower efficiency levels in these european countries. More stringent CO_2 limits induce implicit reductions of cement production.

The efficiency values based on the Direction Distance model in the case of regulation constraints (weak disposability) significantly differ from the corresponding values of Table 6. The application of the Wilcoxon test between efficiency scores of models *M3* and *M4weak* is still significant with a two tailed p statistic equal to 0.002 (value of Wilcoxon statistics 3.59).

As already explained at the beginning of the section, the difference between efficiency levels

Table 6: CEM instance: efficiency scores based on the Direction Distance model without undesirable outputs

Country	**2005**	**2006**	**2007**	**2008**	**Annual average**
Australia	0	0.22784	0.22346	0.21002	0.16533
Austria	0	0.28959	0.18743	0.13195	0.15224
Belgium	0	0	0.02746	0.01332	0.0102
Brazil	0	0	0	0	0
Canada	0.00471	0	0.00878	0.05829	0.01794
China	0	0	0	0	0
Czech Republic	0	0.10073	0.0869	0.08332	0.06774
Denmark	0	0	0	0.00602	0.0015
Estonia	0.17768	0.16848	0.21929	0.4226	0.24701
France	0.10207	0.09017	0.11559	0.09114	0.09975
Germany	0.06471	0.02634	0	0.0391	0.03254
India	0	0	0	0.00941	0.00235
Italy	0	0	0.00855	0.04221	0.01269
Japan	0	0.00148	0	0.01028	0.00294
Norway	0.14757	0.20308	0.16812	0.15097	0.16743
Poland	0	0.20821	0.16491	0.00011	0.09331
Spain	0	0	0	0.02489	0.00622
Switzerland	0.06621	0.07565	0.07832	0.07146	0.07291
Turkey	0.13132	0.1139	0.14005	0.15835	0.1359
U.S.A.	0.10956	0.17357	0.17808	0.19452	0.16393
United Kingdom	0.16541	0.20789	0.20893	0.21948	0.20043
Country average	0.04615	0.08985	0.08647	0.09226	0.07868

under strong and weak disposability assumptions gives the Normative Price. In CEM instance, reported in Table 7, we see an average normative price of 0.01. More in detail, the highest value of normative price is reached in 2005, corresponding to the year of the inception of the EU-ETS. During the period under analysis several non-european countries adopted environmental policies in order to mitigate CO_2 effects. This is confirmed by the 2008 value of normative price. However, globally considered, the differences in efficiency measures under the hypothesis of weak and strong disposability assumptions are statistically significant according to this model formulation (Wilcoxon test statistics equal to 3.06).

Table 7: CEM instance: efficiency measure as undesirable output contraction and desirable output expansion

Country	**2005**		**2006**		**2007**		**2008**		**Annual average**	
	Strong	**Weak**	**Strong**	**Weak**	**Strong**	**Weak**	**Strong**	**Weak**	**Strong**	**Weak**
Australia	0	0	0.18953	0.18953	0.17537	0.17537	0.15829	0.15829	0.1308	0.1308
Austria	0	0	0.20852	0.20852	0.14425	0.14425	0.10284	0.10284	0.1139	0.1139
Belgium	0	0	0	0	0.02746	0.02741	0.00857	0.00857	0.00901	0.009
Brazil	0	0	0	0	0	0	0	0	0	0
Canada	0.00471	0	0	0	0.00878	0.00278	0.05829	0.02097	0.01794	0.00594
China	0	0	0	0	0	0	0	0	0	0
Czech Republic	0	0	0.09104	0.09104	0.0869	0.0852	0.07924	0.07924	0.06429	0.06387
Denmark	0	0	0	0	0	0	0.00475	0.00475	0.00119	0.00119
Estonia	0.17768	0	0.16848	0	0.21929	0	0.39763	0.39763	0.24077	0.09941
France	0.08982	0.08982	0.07778	0.07778	0.10051	0.10051	0.07798	0.07798	0.08652	0.08652
Germany	0.05622	0.05622	0.01762	0.01762	0.07992	0.07992	0.02678	0.02678	0.04514	0.04514
India	0	0	0	0	0	0	0.00941	0	0.00235	0
Italy	0	0	0	0	0.00855	0	0.03428	0.03428	0.01071	0.00857
Japan	0	0	0.00148	0	0	0	0.0096	0.0096	0.00277	0.0024
Norway	0.13813	0.13813	0.18697	0.18697	0.15549	0.15549	0.1402	0.1402	0.1552	0.1552
Poland	0.02539	0.02116	0.20289	0.20289	0.15989	0.15989	0	0	0.09704	0.09598
Spain	0	0	0	0	0	0	0.01957	0.01957	0.00489	0.00489
Switzerland	0	0	0	0	0.00051	0.00051	0	0	0.00013	0.00013
Turkey	0.13132	0.12841	0.1139	0.11058	0.13549	0.13549	0.14508	0.14508	0.13145	0.12989
U.S.A.	0.10956	0	0.17357	0.12148	0.17808	0.1436	0.19016	0.19016	0.16284	0.11381
United Kingdom	0.15156	0.15156	0.18919	0.18919	0.18473	0.18473	0.21031	0.21031	0.18395	0.18395
Country average	0.04211	0.02787	0.07719	0.06646	0.0793	0.06643	0.07967	0.07744	0.06957	0.05955
Normative Price	0.01424		0.01073		0.01286		0.00223		0.01002	

Tables 8 and 9 present the results concerning CLK instance. Following the same lines of CEM instance, in Table 8 we analyze the clinker production efficiency without including CO_2 undesirable output. The results confirm the tendency of the corresponding instance studied with DEA models in Table 4. The average efficiency level is 0.08717, lower than the one in Table 6. In addition, countries like Brazil that are efficient in the CEM instance, results to be one of the most inefficient when referring to the clinker production process only, followed by Australia, Turkey and Italy. Among years, 2008 confirms to be the year with the lowest efficiency score that amounts to 11.595% while in the 2007 is 3.75% higher.

Table 9 presents the efficiency scores of models $M4$ and $M4weak$, directional distance function approaches under strong and weak disposability assumptions respectively. The CO_2 undesirable output is included in the efficiency estimations and the models highlight how the environmental regulation can limit desirable output expansion. The annual average under the hypothesis of strong disposability is equal 0.07993: this means that desirable output could be still increased by an amount of about 8%. In the case of weak disposability assumption, this percentage amounts to 7.5%. This difference in efficiency scores between model $M4$ and $M4weak$ is supported by the Wilcoxon Test with a statistic equal to 3.06 and a p-value equal to 0.0025. This means that in presence of normative constraints, clinker production has a more limited production expansion capability. The most efficient countries, according to this model, are Austria, China, Switzerland and Belgium. With respect to the same instance evaluated with DEA model (see Table 5 in the previous section), the most efficient countries do not vary, except for India which reaches levels of efficiency quite close to the peer units. In fact, according to the explanation expressed in the previous section, we assist again to an efficiency collapse of Brazil. Finally, in order to capture the importance of including undesirable outputs in the clinker process efficiency study, we have compared the annual average of models $M3$ and $M4weak$ for the CLK instance. The Wilcoxon test (value of statistical 3.92 and p-value 0.00009) highlights a significant difference between the two formulations at the 1% significance level.

Table 8: CLK instance: efficiency scores based on Standard Directional Distance model

Country	**2005**	**2006**	**2007**	**2008**	**Annual average**
Australia	0.21811	0.23107	0.24954	0.2882	0.24673
Austria	0	0	0	0	0
Belgium	0	0	0	0.01549	0.00387
Brazil	0.29815	0.30316	0.27332	0.29125	0.29147
Canada	0	0	0.00456	0.06277	0.01683
China	0	0	0.00043	0	0.00011
Czech Republic	0	0.15048	0.0714	0.06664	0.07213
Denmark	0	0.00259	0	0.107	0.0274
Estonia	0.09557	0.13479	0.09704	0.15185	0.11981
France	0.14126	0.18027	0.18026	0.19794	0.17493
Germany	0.09356	0.15464	0.10116	0.16728	0.12916
India	0.00193	0.06061	0.05434	0.07323	0.04752
Italy	0.2217	0.22568	0.22336	0.23409	0.22621
Japan	0	0	0.03698	0.04869	0.02142
Norway	0	0.0651	0.06353	0.05614	0.04619
Poland	0.13993	0.0404	0.05828	0.18043	0.10476
Spain	0.02447	0.03198	0.04443	0.09849	0.04984
Switzerland	0	0.02265	0	0.01111	0.00844
Turkey	0.14283	0.22102	0.16968	0.13391	0.16686
U.S.A.	0	0	0	0.07434	0.01859
United Kingdom	0	0.02772	0.0293	0.17609	0.05828
Country average	0.0656	0.0882	0.07893	0.11595	0.08717

Table 9: CLK instance: efficiency measure as undesirable output contraction and desirable output expansion

Country	2005		2006		2007		2008		Annual average	
	Strong	Weak	Strong	Weak	Strong	Weak	Strong	Weak	Strong	Weak
Australia	0.21811	0.2125	0.21624	0.21624	0.23333	0.23333	0.27354	0.27354	0.23531	0.2339
Austria	0	0	0	0	0	0	0	0	0	0
Belgium	0	0	0	0	0	0	0.00307	0.00307	0.00077	0.00077
Brazil	0.29815	0.29755	0.27928	0.27928	0.24833	0.24833	0.22649	0.22649	0.26306	0.26291
Canada	0	0	0	0	0.00285	0.00285	0.05601	0.05601	0.01471	0.01471
China	0	0	0	0	0.00043	0	0	0	0.00011	0
Czech Republic	0	0	0.13899	0.13899	0.07107	0.07107	0.06494	0.06494	0.06875	0.06875
Denmark	0	0	0.00259	0	0	0	0.09132	0.09132	0.02348	0.02283
Estonia	0.09557	0	0.13479	0.09511	0.09704	0	0.15185	0.1298	0.11981	0.05623
France	0.14126	0.12554	0.17374	0.17374	0.17564	0.17564	0.1795	0.1795	0.16754	0.16361
Germany	0.09356	0.07523	0.14129	0.14129	0.09199	0.09199	0.14898	0.14898	0.11896	0.11438
India	0.00193	0	0.06038	0.06038	0.05434	0.02951	0.07307	0.07307	0.04743	0.04074
Italy	0.2217	0.21972	0.2177	0.2177	0.22336	0.22309	0.21066	0.21066	0.21836	0.21779
Japan	0	0	0	0	0.01712	0.01712	0.02235	0.02235	0.00987	0.00987
Norway	0	0	0.06317	0.06317	0.06042	0.06042	0.05423	0.05423	0.04446	0.04446
Poland	0.13993	0.13951	0.04009	0.04009	0.05597	0.05597	0.10377	0.10377	0.08494	0.08484
Spain	0.02447	0	0.03198	0.00146	0.04384	0.04384	0.09242	0.09242	0.04818	0.03443
Switzerland	0	0	0	0	0	0	0	0	0	0
Turkey	0.13596	0.13596	0.19063	0.19063	0.12859	0.12859	0.0952	0.0952	0.13759	0.13759
U.S.A.	0	0	0	0	0	0	0.07197	0.07197	0.01799	0.01799
United Kingdom	0	0	0.02772	0.01809	0.0293	0.01689	0.17222	0.17222	0.05731	0.0518
Country average	0.06527	0.05743	0.08184	0.07791	0.07303	0.0666	0.0996	0.09855	0.07993	0.07512
Normative Price	0.00784		0.00392		0.00643		0.00105		0.00481	

4.3 Overall comments

In this Section the determinants of efficiency and inefficiency are investigated by country and main differences are reported below. The presence or absence of environmental regulations strongly affects country efficiency scores. According to the computational results of Sections 4.1 and 4.2, European countries that are generally efficient are Austria, Switzerland, Spain, Belgium and Denmark while among the non-Europeans Japan, Canada, China and India results to be almost efficient.

Austria Cement industry in recent years has continuously reduced its specific CO_2 emissions that are very low compared to the other countries thanks to a massive use of alternative fuels (more than 50%). In addition, it has developed a research project in order to reduce the clinker proportion in cement manufacturing. The project aims to study whether and how the optimization of ultra-fine particles (particle size distribution, particle shape and roughness) in cement can substitute clinker content. The expected emissions contractions vary between 5 % and 15%.

Switzerland efficiency can be addicted to a massive use of alternative fuels that, on average, amounts to 45% of total fuel consumption and of alternative raw material. The combination of these policies leads to a lower emission factor per ton of cement. In Spain, cement industry has doubled the utilization of alternative fuels and raw materials in the last decades. In 2008, in facts, alternative fuels accounted for the 15% of the total, while alternative raw materials were the 10% of total use. In the Annual Belgian Cement Association Report 2008, the IEE and IGES indexes show a progressive effort in reducing CO_2 emission and in improving energy efficiency since 2005[10]. Danish cement industry has replaced by at least 40% the fuel energy used in the production of grey cement by alternative fuel. In addition, thanks to its participation to the FUTURECEM project, supported by the Danish National Advanced Technology Foundation, the cement sector has performed full-scale trials on a new type of clinker based on nanotechnology. The clinker will be used in the cement of the future and produce less CO_2 emission. This project was completed in 2010. Again, the combination of all these factors has made Danish cement industry efficient.

As concerning non European countries, different mandatory or voluntary environmental regulations are applied. Japanese Cement Industry is involved in the Voluntary Emissions Trading Scheme, in particular cement industry outperforms the CO_2 emission target imposed by regulation. Among the other efficient countries, India benefits from the progressive abandon of wet technologies in favour of less energy expensive dry processes based on five and six stages pre-heatering and pre-calcination kilns. Note also that main Indian companies agree with the Cement Sustainability Initiative (CSI) launched by the World Business Council for Sustainable Development (WBCSD).

The case of China cement industry is more controversial. On one hand, the recent fast growth of Chinese economy led to huge investments in best available technologies new plant. This development of Chinese cement sector is in part due to foreign investors that operate in emission regulated countries and transfer their production maintaining high efficiency levels. On the other hand it can also be explained by the increase in production of blended cement which requires a lower clinker to cement ratio and reduces energy consumption and CO_2 emissions. As to environmental policies, China has implemented a national Climate Change Program and it is involved in the Asia-Pacific Partnership on Clean Development and Climate Partners with cement industries operating in India, Japan and U.S.A. For all these reasons, the emission factor that is ratio between CO_2 emission and

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[10] IEE stands for *indice d'amélioration de l'efficience énergétique* and IGES stands for *indice de réduction des émissions de CO_2 énergétique (combustibles)*. See Report Febelcem 2009 at page 20, available at http://www.febelcem.be/index.php?id=rapports-annuels

cement production is one of the best performing among the considered countries.
However, the analysis of Chinese cement sector is difficult because of data lacks. Only 5% of Chinese Cement companies agrees with the CSI of WBCSD and data available on National Cement Association only refer to the larger operating companies. It is very difficult to have a full snapshot of the sector, so our results may be affected by data uncertainty.
In Canada the development of cement industry is similar to the one of the U.S.A. cement industry. Regional regulations (like Alberta's Climate Change and Emission Management Act) and voluntary compliance to international environmental programs have forced cement industry to increase their level of efficiency. Differently from the EU-ETS, the Alberta's Act uses an emission intensity approach[11]. This system forces the involved facilities to improve their performance either by reducing their greenhouse gases emissions or by buying credits from the Climate Change and Emission Management Fund at a price of 15 Canadian dollars per each ton of reduced emission.

The ranking of inefficient countries is different with respect to the instance we consider. However, Australia and Turkey show to be inefficient in almost all cases. We first recall that these two countries are not subject to any environmental regulation. The proposal for an emission trading scheme in Australia has been blocked and its possible implementation will be postponed after 2013. Turkey only recently has shown an environmental awareness by ratifying the Kyoto Protocol in2009.

Finally Brazil shows an hybrid behaviour. Depending on the instance under consideration Brazil is either efficient or inefficient. More specifically, the Brazilian cement industry is efficient in the CEM instance both with and without CO_2 undesirable output. The overall cement production process appears to be efficient because the clinker/cement ratio (0.68%-0.70%) is relatively low compared to standard ratio (0.76%-0.80%). These efficiency levels fall down when considering the CLK instance. In fact, the proportion of the alternative fuels is minimal compared to the total use and moreover only starting 2009 a voluntary environmental program has been introduced.

5 Conclusions

In this paper we analyze the impact of CO_2 emissions on the efficiency of the world cement industry using Data Envelopment Analysis (DEA). This work differs from literature since it analyzes 21 countries covering the 90% of the world cement production during the period 2005-2008. Traditional industrialized countries are compared with emerging producers like India, China, Turkey and Brazil.

There are different approaches to incorporate undesirable pollutants in DEA models. In this work a classical DEA model with undesirable factor treated as inputs and a directional distance function model where CO_2 emission are undesirable output have been considered. The same kind of models have been implemented without considering undesirable factors. The differences resulting from the comparison of these models with and without undesirable factors are statistically significant (as highlighted by a Wilkonox Rank Sum Test). From these statistical tests we can deduce that CO_2 emissions modify the efficiency levels and they can not be excluded in the efficiency evaluation of the worldwide cement industry.

Two different instances have been formulated in order to understand efficiency and inefficiency causes. The first instance (CEM) describes efficiency of the whole cement production process taking energy, raw materials, clinker, capital and labour as inputs, cement production as desirable output and CO_2 emissions as undesirable factor (assumed to be input or output according to the model

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[11] The emission intensity measures the amount greenhouse gases generated per unit of economic output.

studied). The second instance (CLK) studies the clinker production sub-process. We choose to also analyze clinker production because it is most critical phase of the entire cement production process: CO_2 emissions are mainly generated by chemical reactions in the calcination of raw materials. Focusing on this phase we avoid imbalances in efficiency scores due to plant relocation or blended cement production. Countries in which environmental regulations curb CO_2 emissions can decide to transfer their facilities in unregulated regions in order to limit the emission costs without changing their production volumes. In the case of the cement production, companies can move their clinker plants.

Our analysis has shown that the efficiency levels mainly depend on decisions to invest in alternative raw materials and alternative fuels both in the case of mandatory and voluntary emission regulated countries. Among European countries, compulsory involved in the EU-ETS, Belgium, Austria, Denmark and Spain appear to be efficient both in the CEM and CLK instances. Substitution levels in raw materials and fuels, significant investments in advanced technology and research and development programs (like in Austria and Denmark) are the determinants of this success. A similar reasoning applies to Switzerland and Japan, where the use of alternative raw materials and fuels is about the 50% of the total quantities. Among emerging countries that face fast growth of cement production in recent years, China and India show high efficiency levels. This feature can be explained by two different factors: plants with more efficient technologies (progressive substitution of small wet process plants with bigger and dry technology ones), investments in the production of blended quality cements requiring less proportion of clinker. The case of China cement industry, however, requires careful attention because of lack or fragmentary data. Brazil efficiency results confirm the importance of considering both CEM and CLK instances: being inefficient in the CLK case it becomes a peer unit in CEM instance. Finally, countries without any environmental regulation have no incentive to improve their ecological performance. This is the case of Australia and Turkey.

The two classes of models have been tested under strong and weak disposability assumptions. Strong disposability corresponds to an unregulated framework while weak disposability assumption imposes normative constraints. The differences in efficiency scores is denoted as Normative Price in the directional distance approach. Our results show that this difference is statistically significant and the Normative Price tend to decrease over time. This means that countries are able to progressively adapt their technologies to environmental targets.

Further developments are in the direction of enlarging the actual dataset by including more cement producing countries, useful to increase the discrimination power of the DEA models and to modify input and output data of the instances. In this light a further analysis will consider more than one undesirable factor. In recent years, in facts, national authorities intend to extend environmental regulation to a wider class of greenhouse gases like NO_x, SO_2 emissions.

A Appendix A: Sources of Database

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

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

Australia

Australian Cement Federation. *Australian cement industry sustainability Report.* 2009. Available at: http://cement.org.au/publications/environment-sustainability-reports

Australian Cement Federation. *CIF Technical Reports. FastFacts.* 2009-2005. Available at: http://cement.org.au/publications/cif-technical-reports

Australian Cement Federation. *CIF Technical Reports. Review of the Technology Pathway for the Australian Cement Industry 2005 - 2030.* 2007.
Available at: http://cement.org.au/publications/cif-technical-reports

Austria

Vereinigung der Osterreichischen Zementindustrie (VOZ). *Nachhaltigkeitsbericht 2008/2009 der sterreichischen Zementindustrie.* 2008.
Available at: http://www.zementindustrie.at/file_upl/voez_nhb0809.pdf

Mauschitz G. *Emissionen aus Anlagen der sterreichischen Zementindustrie Berichtsjahr 2007.* 2007.

Belgium

Febelcem. *Standpunten. De Belgische cementindustrie.* 2006.
Available at: http://www.febelcem.be/fileadmin/user_upload/rapports_annuels/ nl/Jaarverslag-cementindustrie-2006-nl.pdf

Febelcem. *Standpunten. De Belgische cementindustrie.* 2008.
Available at: http://www.febelcem.be/fileadmin/user_upload/rapports_annuels/ nl/Jaarverslag-cementindustrie-2008-nl.pdf

Febelcem. *Milieurapport van de Belgische cementnijverheid.* 2006.
Available at: http://www.febelcem.be/index.php?id=rapports-environnementaux\&L=2

Febelcem. *Rapport annuel de l industrie cimentiére belge.* 2008-2009.
Available at: http://www.febelcem.be/index.php?id=101\&L=1

Brazil

Sindacato Nacional da Indústria do Cimento. *Relatórios Anuals.* 2008.
Available at: `http://www.snic.org.br/`

Canada

Natural Resources Canada. Office of Energy Efficiency. *Energy Consumption Benchmark Guide: Cement Clinker Production.* 2001.
Available at: `http://oee.nrcan.gc.ca/publications/industrial/BenchmCement_e.pdf`

Cement Association of Canada. *Canadian Cement Industry. Sustainability Report.* 2008.
Available at: `http://www.uaecement.com/articles/Canadiancement2008.pdf`

Cement Association of Canada. *Canadian Cement Industry. Sustainability Report.* 2010.
Available at: `http://www.cement.ca/`

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`

Czech Republic

Data and several publications are available at `http://www.svcement.cz/`

Denmark

AalborgPortland (Cementir Holding). *Environmental Report.* 2009.
Available at: `http://www.aalborgportland.com/media/annual_report/environmental_report_2009.pdf`

AalborgPortland (Cementir Holding). *Annual Report.* 2009.
Available at: `http://www.aalborgportland.com/media/annual_report/annual_reporta_2009.pdf`

Estonia

Kunda Nordic (HeidelbergCement Group). *Sustainability Report. Continuous development is the basis of sustainability.* 2007.
Available at: `http://www.heidelbergcement.com/NR/rdonlyres/ 7C8311B6-51F6-418A-BCBA-A0787B9923CB/0/Sust_Kunda_ENG_2007.pdf`

Further information are available at:
`http://www.heidelbergcement.com/ee/en/kunda/keskkond/sustainability_report.htm`

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`

VDZ Deutsche Zementindustrie. *Umweltdaten der deutschen Zementindustrie.* 2008.
Available at:
`http://www.bdzement.de/fileadmin/gruppen/bdz/Themen/Umwelt/Umweltdaten_2008.pdf`

Bundesverband der Deutschen Zementindustrie e.V. and Verein Deutscher Zementwerke e.V. *Zementrohstoffe in Deutschland.* 2002.

VDZ Deutsche Zementindustrie. *Monitoring-Bericht 2004-2007. Verminderung der* CO_2*-Emissionen.* 2008.

Further information are available at: `http://www.bdzement.de/167.html`

India

Cement Manufacturers' Association. *Annual Report.* 2008-2009.

Ghosh, A., M. Sabyasachi, I. Rohit, A. Gupta. *Indian Cement Industry. Profitability to come under pressure as new capacities take concrete shape.* 2010.

Saxena, A. *Best Practices & Tchnologies for energy efficiency in Indian Cement Sector.* Presentation.

De Vries, H.J.M., A. Revi, G.K. Bhat, H. Hilderink, P. Lucas. *India 2050: scenarios for an uncertain future.* Netherlands Environmental Assessment Agency, n. 550033002, 2007.

Ghosh S.P. *Energy Efficiency Initiatives, Estimation of CO_2 Emission and Benchmarking Energy and Environmental Performance in Indian Cement Industry.* Presentation at the "Workshop on CO_2 Benchmarking and Monitoring and CDM Benchmarking in Cement Industry", 2007.

Singhi, M.K., R. Bhargava. *Sustainable Indian Cement Industry.* Presentation at the "Workshop on International Comparison of Industrial Energy efficiency", 2010.

Chattopadhyay, S. *The Cement Sustainability Initiative.* Presentation at the "IEA-BEE workshop on energy efficiency", 2010.

Italy

Aitec. *Relazione Annuale.* 2005-2009. Available at: `http://www.aitecweb.com/`

Japan

Data are available at `www.jcassoc.or.jp/cement/2eng/ea.html`

Norway

Norcem (HeidelbergCement Group). *Rapport om Baerekrafting Utvikling. Vart ansvar a bygge for framtiden.* 2007.
Available at: `http://www.heidelbergcement.com/no/no/norcem/sustainability/Rapporter/index.htm`

Further data are available at
`http://www.heidelbergcement.com/no/no/norcem/sustainability/Rapporter/index.htm`

Poland

Data available at `http://www.polskicement.pl/` for several years.

Dejaa, J., A. Uliasz-Bochenczykb, E. Mokrzyckib. *CO_2 emissions from Polish cement industry.* International Journal of Greenhouse Gas Control Vol. 4, p. 583588, 2010.

Spain

Annual reports are available at `http://www.oficemen.com/reportajePag.asp?id_rep=634` for several years.

Switzerland

CemSuisse. *Jahresbericht.* 2010. Available at: `http://www.cemsuisse.ch/cemsuisse/index.html`

CemSuisse. *Kennzahlen.* 2010. Available at: `http://www.cemsuisse.ch/cemsuisse/index.html`

Turkey

Data are available at: `http://www.tcma.org.tr/index.php?page=icerikgoster\&menuID=1`

U.S.A.

Portland Cement Association. *Report on sustainable manufacturing.* 2009. Available at: `www.cement.org/smreport09`

USGS. Science for a changing world. *Minerals Yearbook. Cement (Advance Release).* 2007. Available at: `http://minerals.usgs.gov/minerals/pubs/commodity/lime/myb1-2007-lime.pdf`

Further data available at:
`http://www.cement.org/index.asp`,
`http://minerals.usgs.gov/minerals/pubs/commodity/cement/`

United Kingdom

British Cement Association (BCA). *Performance reports.* 2003-2008. Available at: `http://cement.mineralproducts.org/downloads/performance_reports.php`

Quarry Products Association (QPA). *Sustainable Development Report Summary.* 2008. Available at: `http://www.mineralproducts.org/documents/QPA _SD _08 _Rep.pdf`

British Geological Survey. Mineral Profile. *Cement Raw Materials.* 2005. Available at: `http://www.bgs.ac.uk/downloads/start.cfm?id=1408`

Other data and information are available at `http://cement.mineralproducts.org/downloads/`

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