Potential For Energy Conservation And Reduction Of CO_2 Emissions In The Brazilian Cement Industry Through 2015

Jeferson Borghetti Soares and Maurício Tiomno Tolmasquim
Energy Planning Program – Post-Graduate Engineering School - Rio de Janeiro Federal University

ABSTRACT

The cement industry is characterized by intensive energy consumption throughout its production stages which, together with the calcination of its raw materials, accounts for significant amounts of greenhouse gases (GHG) emissions. In 1996, the Brazilian cement industry consumed 4.3% of the energy required by the industrial sector, contributing over 22 Mtons (Million of tons) of CO_2.

The prospects for growth in this sector in Brazil indicate rising demands for fossil fuels, with a consequent upsurge in emissions. The purpose of this article is to present the prospects for energy conservation in the Brazilian cement industry through to 2015, taking into account the introduction of new production technologies in this sector, the use of waste and low-grade fuels, cogeneration, the use of additives, and other measures, based on a technical and economic energy demand simulation model.

Introduction

The cement industry is one of the main sectors responsible for the emission of greenhouse gases (GHG), specifically CO_2, due to the calcination of raw materials for the production of Portland cement, in addition to consumption of fuels needed to maintain the high temperatures required by these processes. According to Holdren and Pachauri (1991) *apud* Rosa et al (1996), this industry accounted for 2% of total accumulated global emissions in world due to anthropic sources.

In 1996, the Brazilian cement industry - which accounts for around 1% of Brazil's industrial output and approximately 20% of the Added Value for the Non-Metal Minerals Products Industry - consumed 3.44 Mtoe (Million tons of oil equivalent) corresponding to some 4.3% of energy consumption for the entire industrial sector (MME 1997), consisting largely of fuel oil (42.0%) and electricity (30.4%). Taking into account the portion due to process emissions, in 1996, this sector emitted over 22 Mtons of greenhouse gases, with CO_2 accounting for over 99% of the total.

A crucial sector of the national economy, its performance is frequently associated with the economic health of a country. Brazil has a low *per capita* cement consumption level (221.6 kg/inhabitant), with massive growth potential. In 1996, this indicator rose 22.1% over the previous year (SNIC 1996). At the international level, Brazilian output ranked twelfth in 1995, with China heading up the global production ranking at over 445 Mtons a year.

Most of Brazil's cement output consists of Compound Portland Cement (77.1%), used for normal concrete construction. The cements with the highest levels of additives permitted in the standards – Blast-Furnace Portland Cement (10.1%) and Portland-Pozzolan Cement (7.1%) – jointly account for a 17%-20% share of Brazilian output.

Energy Use And GHG Emissions By The Brazilian Cement Industry

The most energy intensive stage in cement production is without doubt clinker production, with the energy sources most widely used at the moment being fuel oil (42.0%) and electricity (30.4%) (MME 1996). The latter is used mainly to drive electric motors, and to a lesser extent for thermal energy requirements and lighting (MME/FDTE 1995). Fuel oil is used mainly for heating raw materials in order to bring about calcination and clinker production reactions. Other outstanding factors this year are the use of charcoal and coal at 8.9% and 16% respectively (MME 1997). Other energy sources play a modest role in terms of total consumption, used mainly for thermal energy requirements in furnaces and kilns.

Figure 1 shows the history of energy consumption by source in the Brazilian cement industry from 1980 through 1996. During this period, the use of fuel oil dropped sharply, due to the signature of the Protocol for the Reduction and Replacement of Fuel Oil Consumption in the Cement Industry, prompted by the second oil embargo in 1979.

An examination of the development of overall specific energy consumption by the Brazilian cement industry from 1980 through 1996 shows a downtrend over time, dropping from 942 kcal/kg of cement in 1980 to 732 kcal/kg of cement in 1996, reflecting an annual improvement rate of 1.56%. This marked drop in specific consumption of around 22.3% was achieved through a set of factors including the shut-down of wet process plants and/or conversion to dry process operations, as well as increased use of cement additives.

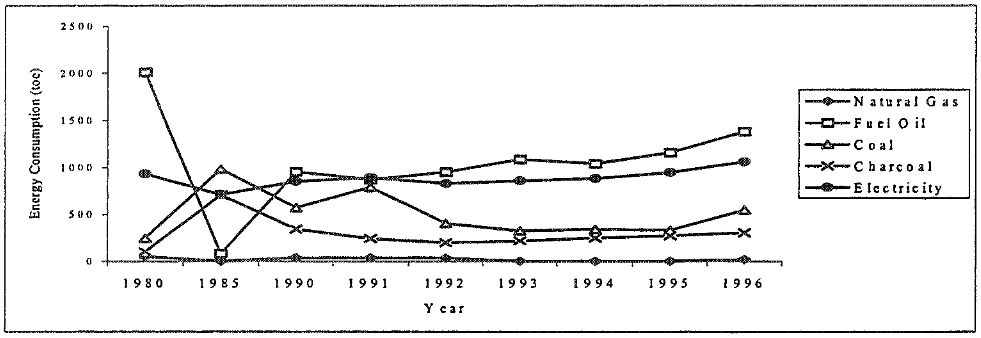

Figure 1. Development of consumption by source, 1980-1996 for selected years. (Source: Prepared on the basis of data from the MME, 1997).

From 1982 through 1988, the amount of additives noted in the sector for Compound Portland Cement ranged from 0% to 23%, resulting in a drop in the average specific consumption value from 962 kcal/kg of cement to 791 kcal/kg of cement. Moreover, in that period, the use of additives was also responsible for drop this average consumption from 384 kcal/kg of cement to 265 kcal/kg of cement for Blast Furnace Portland Cement and from 802 kcal/kg of cement to 748 kcal/kg of cement for Portland-Pozzolan Cement (Fonseca, Carmo & Terada 1992).

In terms of production technology, two major processes are basically used to manufacture clinker, known as dry process and wet process. They differ mainly in terms of the preparation of the raw materials, introduced in the form of powder with a low moisture level, or blended with water, respectively. However, the clinker produced by either of these processes is essentially the same, with no difference in the quality of the final product.

The main advantage of the dry process is an average specific heat energy consumption to 800 kcal/kg of clinker in Brazil (SNIC 1998) while for wet processing this figure hovers around 1200 kcal/kg of clinker. This is an important comparative advantage for an industry where fuel expenditures account for some 18%-20% of total costs and 35% - 40% of variable costs (Santi 1997). In Brazil, the dry process is more widely used, accounting for over 98% of the nation's cement output in 1996 (SNIC 1998).

Among the final energy use categories, the principal application is for thermal energy requirements (68.3%) represented by the rotating clinkering kiln. Driving power ranks second for consumption, taken up mainly by electrical start-up mechanisms for electric engines in machinery such as crushers, mills, conveyor belts etc. At a more marginal level is the start-up of combustion engines in excavators and trucks, with diesel oil used mainly for this, at around 97% of the total consumption of this energy source (MME/FDTE 1995). In 1996, the sector posted specific consumption of 105 kWh/ton of cement produced. From 1980 onwards, this figure dropped by some 12%, fluctuating over the period, particularly between 1992 and 1994. There is a wide range of performance levels for this indicator, with some plants operating at 90 kWh/ton of cement and other with specific consumption topping 200 kWh/ton.

The difference noted in electricity consumption between the various types of process derives from the manner of use for this energy source, as well as preparation and drying (when necessary), preparation and grinding the raw materials and cement, the exhaust system and the electrostatic precipitators (Silva & Nebra 1996). For cement production plants with specific electricity consumption ranging between 100 and 130 kWh/ton of cement, the typical use percentage distribution during the production stages is 3% for preparation of raw material; 32% for preparation and grinding of untreated material; 21% for blending, clinkering kiln and cooling; 41% for finish grinding; 2% for general and auxiliary jobs and 1% for lighting. Specific electricity consumption for each stage of the process thus varies greatly according to the technology used, as well as in function of the characteristics of the raw materials and the final products obtained (Silva 1994). In the global context, the Brazilian cement industry is in a mid-field position in terms of energy consumption rates (**Figure 2**).

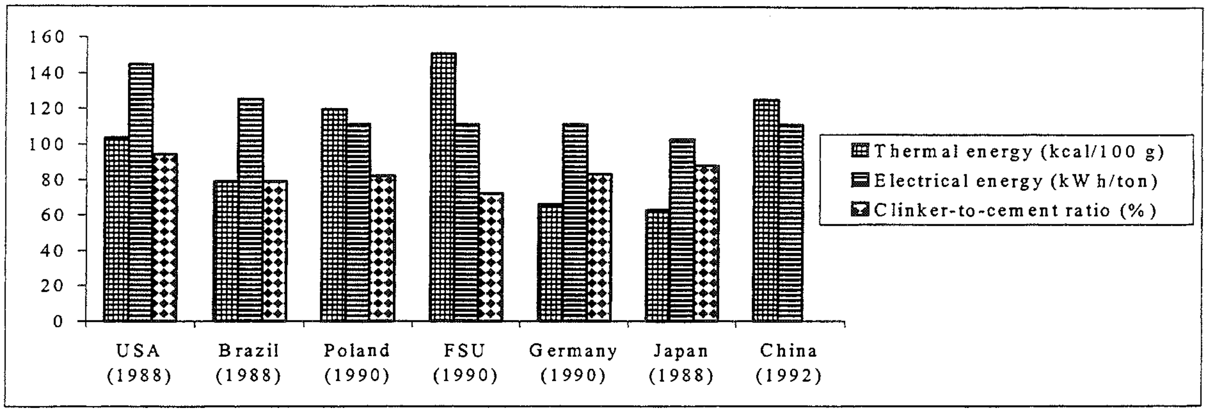

Figure 2. Energy consumption indicators in the cement industry for selected countries. (Source: Prepared on the basis of data from: WEC 1995; Silva 1994).

Carbon dioxide is main contribution by this sector to GHG emissions, accounting, on a mass basis, for over 99% of the total with minimal contributions from gases such as nitrogen oxides, methane and carbon monoxide. From 1980 through 1996, the specific emissions of CO_2 per ton of cement produced due to burning fossil fuels dropped by 18.43%, down from 0.331 ton of CO_2 per ton of cement in 1980 to around 0.270 ton of CO_2 per ton of cement in 1996. Added to this is the contribution made by the untreated materials decarbonation process, which reached a global rate of 0.797 ton of CO_2 per ton of cement in 1996. This reflects the improved energy performance of this sector due to the adoption of more efficient production processes, although these results could be somewhat undermined through the replacement of fuel oil by coal under the Protocol signed in the 1980s when the use of fuel oil dropped most steeply parallels the rising rates for specific emissions due to the replacement by coal, with a higher carbon emission factor per energy unit.

Simulation Model For Energy Demand And GHG Emissions

The simulation of energy demands and CO_2 emissions in the Brazilian cement industry over the period was estimated by fine-tuning a component for this sector found in the Integrated Energy Planning Model (IEPM) developed at COPPE/UFRJ (Tolmasquim & Szklo 1999).

The structure of this model follows the breakdown of the Portland Cement production process into five modules: 1) raw materials quarrying and crushing; 2) milling and blending of untreated raw materials; 3) homogenizing, clinker production and cooling; 4) finish grinding; and 5) other uses (**Figure 3**). This final stage includes uses such as lighting, as well as general and auxiliary jobs. In addition to these modules, a macro-economic module is included, which is designed to allow estimations of the activity levels of the sector (physical output), taking into account the effect of alterating the GDP compositon, based on macro-economic data, in order to estimate physical output for the year under study. This structure is fully coherent with the characteristics of this infrastructure sector, which reflects a close correlation with GDP development, and a performance that is generally more marked than that of the economy overall, meaning that during periods of economic growth it expands more than the country in general, and during times of recession, its performance drops below that of the GDP as a whole. The physical output for the year *t* then is calculated from the relationship: $Prod_t = (VA/PI)_{t*} (PI/VU)_t$ where VA is the Added Value; PI is the Industrial Product and VU is related to the ratio Added Value/physical output.

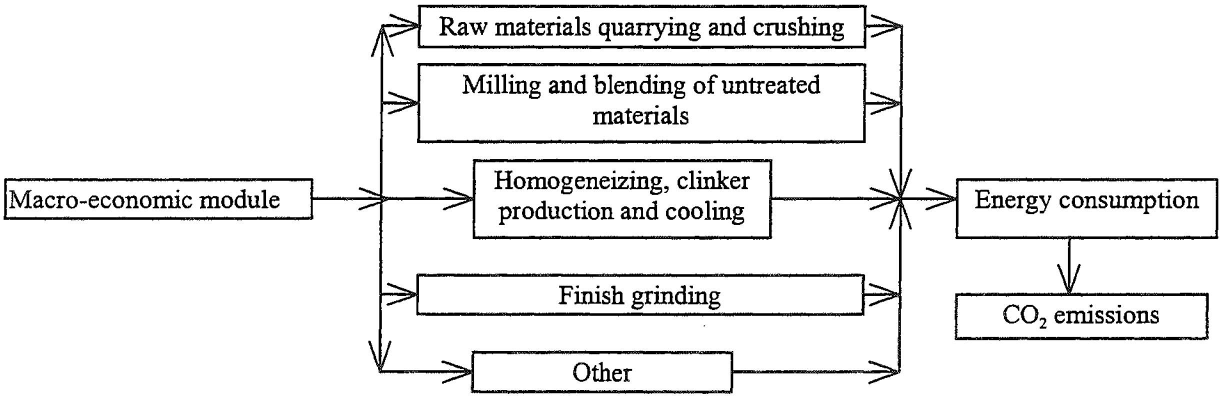

Figure 3. Simplified structure of the technical and economic model IEPM.

The division into modules is justified because this approach allows the decision variables to be taken under consideration almost down to the equipment level, which allows the efficiency of energy sources to be handled by production process. It would be difficult to take a global approach to this sector, as there is a wide range of variation between the raw materials quarrying stage which predominantly uses electricity, while heat-based sources such as fuel oil and coal are used in the rotating kiln. This means that the calculation of an average index would not provide adequate representation for a study of this sector.

Based on these production levels, and with the combination of specific consumption coefficient for usable energy – closed to conversion efficiency in equipments and can be recalculated during the subsequent year in accordance with the hypothesis adopted for the development of the sector – we obtain total energy demand in year *t* into module *i* for fuel *j* according to: $EF_{ijt} = EU_{ijt} * PF_{ijt} / \eta_{ijt}$ where η_{ijt} is the energy conversion efficiency depending on the usage, fuel and technology. Moreover, the module "homogenizing, clinker production and cooling" calculates total energy demand from a relationship that takes in account technological profiles of production. According to clinker production technology, for instance, wet or dry process, input data includes intermediate specific consumption, in kcal/kg of clinker, allowing the model to obtain final product specific consumption in kcal/kg of cement.

The indicators used to forecast energy demands are based on usable energy coefficients per physical production unit. The selection of an indicator based on the usable energy represents the real amount of energy required to carry out a task and allows hypotheses to be drawn up on gains in efficiency due to the introduction of new technologies, as well as inter-energy substitution, by altering the share of each energy source in the final use, assigned to a specific destination, whether as driving power, process heat or for thermal energy requirements, for example. In addition to inter-energy substitution, the model allows consideration of the impact of the introduction of product mix changes and moreover waste materials left over from other activities and used as cement additives. The total amount of aditives then is calculated considering the individual amount of additives and product mix by cement kind. Further, an electricity cogeneration module and another module for calculating GHG emissions are included.

Energy Use Scenarios Through To 2015

In order to obtain an overview of the development of this sector over a twenty-year period, two macro-economic business-as-usual scenarios were adopted, backed by two alternative scenarios for each business-as-usual scenario, and whose basic hypotheses assume different levels of economic activity, one worst-case and the other best-case, drawn up by official planning agencies with acknowledged competency in this matter: respectively the National Bank for Economic and Social Development (BNDES) and the Institute for Applied Economic Research (IPEA). This correlation of national economic activity levels with the performance of a nation's cement industry is particularly useful, with a reasonable level of dependence noted between them as this is a sector that depends heavily on infrastructure development in Brazil. The use of development scenarios highlights trends in energy performance indicators over the longer term and helps define practical limits for the planning and implementation of actions fostering energy efficiency and mitigating GHG emissions.

In terms of energy use in the business-as-usual scenarios a trend line was extended from the recent past of this industry, particularly in 1990-1996, with no crises such as oil embargoes or conduct prompted by such difficulties. This means that the distribution of the use of sources was taken as retaining the same proportions as those noted currently within this sector, meaning that there would be no appreciable inter-energy substitution over the period. The main hypothesis adopted in the business-as-usual scenarios may be noted in the Table 1.

Table 1. Summary of principal hypothesis adopted in the business-as-usual scenarios.

Variable	Low Growth	High Growth
GDP growth rate (% p.a.)	**3.6**	**5.5**
% Industrial Output	**1.4-1.5**	**1.0-1.1**
% Energy Sources (except kiln)	**Same proportions as today**	
% Waste and Low Grade Fuels	**Minimal**	
% Dry Process Technology	**100% from 2000 onwards**	
Specific consumption (kcal/kg clinker)	**Reaches 730 kcal/kg of clinker in 2001**	
Electricity Efficiency	**Trend-Based**	
Amount of Additives in Cement	**Close to current proportions**	
Product Mix	**Same as current proportions**	
Electricity Cogeneration	**Not in Use**	

Table 2- Summary of the hypothesis adopted in the alternative scenarios.

Variable	Technical Potential (IA and IIA)	Market Potential (IB and IIB)
% energy sources (except kiln)	**Same proportions as today**	
% waste and low grade fuels	**20% petroleum coke**	**20% in 2007**
% dry process technology	**100%**	
Specific consumption (kcal/kg clinker)	**640 kcal/kg**	**640 kcal/kg in 2006**
Electricity efficiency	**98 kWh/ton**	**103 kWh/ton in 2015**
Amount of additives in cement	**Maximum proportions allowed in rules**	**65% (PC-III) and 34% (PC-IV)**
Product mix	**56.6% (PC-III) and 29.8% (PC-IV)**	**13.5% (PC-III) and 18.7% (PC-IV)**
Electricity cogeneration	**100%**	**50% of the sector in 2015**

The alternative scenarios presented in this paper include a set of hypothesis that portray a context where improved use of energy may be noted in a more aggressive manner than usual. **Table 2** gives a summary of the hypothesis adopted in these scenarios. The technical potential scenarios (IA and IIA) assume simultaneous instantaneous conversion of current systems to more efficient technologies and best practices from the year 2000 onwards. Further, specific consumption in **Table 2** covers untreated mineral blending. In terms of market potential, this corresponds to an intermediate scenario between the business-as-usual scenarios, the trend-based scenarios and the theoretical energy efficiency technical potential scenarios. These hypotheses are based on situations noted in countries that are more advanced in technological terms within this sector, or even more aggressive behavior noted in the Brazilian industry, for example with cement additives. Essentially, the technical potential and market scenarios differ in terms of the penetration rates for more efficient equipment and practices. The technological options covered here include:

a) **Use of high-yield engines**: results in efficiency gains of 84%-96%, compared to standard motors at 77%-94%;

b) **Variable speed drives:** help reduce load variations, for electricity savings of 20%-50% in the operations;

c) **Grinding systems:** Replacement of roller-press mills, achieving consumption rates of around 19 kWh/ton (Hunter 1997 *apud* COPPE 1998);

d) **Use of closed grinding circuits:** In Brazil, some 25% of the facilities have the potential to use these circuits (Santi 1997);

e) **More efficient clinker production technologies:** Penetration of precalciner technology, with an 86% potential substitution in Brazilian plants (SNIC 1998). The use of mineral mixtures in untreated products is also considered, resulting in fuel saving of 58 kcal/kg of clinker (Silva & Nebra 1993);

f) **Clinker coolers:** penetration of grate coolers, resulting in efficiency gains of 60%-75% (Buzzi & Sassone 1993);

g) **Electricity co-generation:** re-use of exhaust gases may result in electricity production rates of 21.1 kWh/ton of clinker (CEMIG 1992);

h) **Solid wastes from other activities:** includes the use of waste and low-grade fuels and the use of cement additives in a broader manner than that currently in use;

i) **Inter-energy substitution:** shifting the share held by coal and fuel oil to natural gas.

The results obtained for the scenarios taken under consideration are given in **Table 3,** corresponding to cumulative results for period 1995-2015. In all scenarios, the energy consumption growth rates and GHG emissions are lower than those noted for physical production and GDP growth in the corresponding business-as-usual scenario, resulting in energy-production demand elasticity of less than one.

The use of alternative fuels (ie, solid wastes from other activities) represents around 20%-29% of the total final energy savings over the period, showing this to be a reasonably interesting alternative for both the sector and the country as a whole, as this reduces the need for oil imports and consequently helps even out the balance of trade. Similarly, dry process technology with precalciner offers great potential for use in Brazil as 86% of this sector still does not yet use it, particularly as this is a technology that is well-adapted to burning waste and low-grade fuels.

Table 3. Summary of results of energy demand simulations for the cement industry.

	Low Growth Scenarios			High Growth Scenarios		
Variable	I (BAU)	IA	IB	II (BAU)	IIA	IIB
Growth rate (% p. a.)						
Physical Output	6.8			8.5		
Energy Demand	6.5	4.1	5.1	8.1	5.7	6.7
GHG Emissions	6.6	2.8	5.0	8.3	4.4	6.6
Saving in fuels and emissions						
Solid Wastes (Mtoe)	-	9.4	6.9	-	10.2	8.7
Additives + technology (Mtoe)	-	24.7	11.7	-	29.8	10.9
CO_2 Emissions (Mton)	-	400	202	-	480	245

Table 3 (cont.). Summary of results of energy demand simulations for the cement industry.

	Low Growth Scenarios			High Growth Scenarios		
Variable	I (BAU)	IA	IB	II (BAU)	IIA	IIB
Electricity savings						
Gains in efficiency (Mtoe)	-	5.4	3.9	-	6.6	4.6
Cogeneration (Mtoe)	-	2.6	1.3	-	3.1	4.9
Physical Indicators						
Heat consumption (kcal/kg)	636	328	450	636	328	450
Electricity Consumption - (kWh/ton)	113	98.0	103	113	98.0	103
CO_2 Emissions (ton/ton cement)	0.630	0.306	0.463	0.630	0.306	0.463

Under the low growth scenario, the technical potential for energy conservation is around 42.1 Mtoe (obtained adding electricity and fuels savings showed in the **Table 3**), equivalent to a reduction of 31.2% in total consumption. Similarly, in a faster growth scenario for the economy (scenario IIA), the technical potential for energy savings reaches 49.8 Mtoe, equivalent to 32.3% of total consumption in relation to scenario II (High growth scenario-business as usual).

The electricity conservation measures introduced by the sector would result in savings of 5.4-6.63 Mtoe (a drop of 11.5%-12.6% of the total), resulting specific electricity consumption of 98 kWh/ton of cement from the year 2000 onwards for both economic growth scenarios (scenarios IA and IIA). In terms of specific heat-energy consumption, this reaches 328 kcal/kg of cement - 48.3% lower than the business-as-usual scenario. This improvement is a result of the assumed reduction in specific consumption through the introduction of more efficient clinker production technologies and principally through the shift from regular and compound Portland Cement to special cements such as Blast-Furnace Portland Cement and Portland-Pozzolan Cement.

The technical reduction potential of CO_2 emissions varies between 44.5%-45.8% of the total, in relation to the business-as-usual scenarios, corresponding to around 400 Mtons to 480 Mtons, some 26 times the amount of emissions in the base-year. The main factor behind this appreciable reduction was the use of the amount of additives to the maximum of their potential, which also represents fossil energy savings in the kiln, for clinkering reactions. Making good use of the amount of additives to Portland Cement, in addition to greater participation by Blast-Furnace Portland Cement and Portland-Pozzolan Cement all make a decisive contribution to reducing specific heat-energy consumption.

In the market potential scenarios (scenarios IB and IIB), the improvement noted in specific heat consumption is due largely to the introduction of more efficient technologies, making the best possible use of cement additives, and moving away from traditional types of cement to special cements (blast-furnace and pozzolan). Altogether, Blast-furnace and pozzolan cements account for 32% of total output from 2000 onwards, helping reduce specific total energy and heat energy consumption to 636 and 450 kcal/kg of cement in 2015 respectively. The percentages for substitution and additives cover only regions where raw materials and waste materials are available for this purpose, as high transportation costs hamper widespread use of this practice in other parts of Brazil.

As already mentioned, these results for the market potential scenarios fall between those obtained for the business-as-usual scenarios and the technical potential scenarios. For the low growth scenario (Scenario IB), the market potential indicates a drop in energy demands from 23.9 Mtoe (18.9% of the total between 1995-2015), while the high growth scenario (Scenario IIB) puts this reduction at 29.1 Mtoe (18.8%).

In terms of electricity consumption, the conservation measures introduced in the market potential scenarios allow specific rates to be reached of 103 kWh/ton of cement. The difference noted in these figures for the technical potential and market scenarios is due to the different penetration rates of more efficient equipment, due to differences in economic feasibility found at COPPE (1998).

Conclusions

In all scenarios, the reduction in CO_2 emissions is relatively significant, over two hundred million tons. This reduction is strongly influenced by rising levels of additives as the principal factor is the emissions from the decarbonation of the raw materials. The use of waste and low-grade fuels boosts the level of emissions, due to a higher emission factor, although this results in savings for other traditional fuels such as coal and fuel oil, in addition to offering an alternative solution for the disposal of solid wastes.

In terms of electricity consumption, the gains in efficiency deriving from the implementation of the technical options considered represents most of the potential reduction in specific consumption. Additionally, electricity co-generation based on the heat content of exhaust gases - although not making this sector self-sufficient in terms of this input material based on the bottoming system - has nevertheless proven reasonably attractive, with reductions of up to 14% in power generation demands by this sector.

Despite the guesstimates and uncertainties involved in any analysis of this type, the figures obtained offer an indication of the impressive potential for reducing energy demands and consequently CO_2 emissions. These figures show that through the introduction of more efficient production technologies such as a precalciner kilns and grate coolers, together with larger amounts of additives, it would be possible to reduce the demand for fuels by 10.9-24.7 Mtoe, while these savings would reach 6.9-10.2 Mtoe through the use of waste and low-grade fuel. Additionally, there is obviously marked potential for reducing CO_2 emissions by 200-400 Mton, cutting the specific emission rate from 0.652 ton of CO_2 per ton of cement in base-year to 0.306-0.463 ton of CO_2 per ton of cement in 2015 in alternative scenarios.

Actions designed to foster energy conservation and mitigate GHG emissions should thus assign top priority to boosting the amount of additives and the introduction of more efficient clinker production technologies. Additionally, measures based on the rational use of electricity, in parallel to the introduction of more sophisticated technologies and co-generation facilities, will lighten demands on the power generation sector, delaying environmental impacts. According to the figures obtained in this simulation, the total possible electricity savings range between 5.2–9.7 Mtoe, or 17.9–33.4 TWh.

Acknowledgements

Authors are grateful to valuable suggestions given by Alexandre S. Szklo during the thesis work.

References

Buzzi, Von S.; Sassone, G. 1993. *Optimierung des Klinkerkühlerbetriebs*. (*Optimization of Clinker cooler operation*). Revised Text of a lecture to the VDZ Congress'93. Düsseldorf. Germany.

[CEMIG] Companhia Energética de Minas Gerais. 1992. *Cogeração no setor cimenteiro*. Conselho Estadual de Energia. Governo do Estado de Minas Gerais. Belo Horizonte. Brasil.

[COPPE] Coordenação dos Programas de Pós-graduação em Engenharia. 1998. *Estimativa do potencial de conservação de energia elétrica pelo lado da demanda no Brasil*. Projeto PROCEL/COPPETEC. Programa PNUD BRA/93/032. Relatório Final. Rio de Janeiro. Brasil.

Fonseca, M. A. S.; Carmo, A. J. B.; Terada, O. A. 1992. "Consumo energético na indústria brasileira de cimento" In *Seminário CEE/Brasil - Setores industriais intensivos em energia*. IPT/SP. São Paulo. Brasil.

Marciano J. E.; Kihara, Y. 1997. "*Looking Green*". World Cement. n^{0} 27. April.

[MME] Ministério das Minas e Energia. 1997. *Balanço Energético Nacional*. Brasília. Brasil.

[MME/FDTE] 1995. *Balanço de Energia Útil - Modelo de Avaliação do Potencial de Economia de Energia*. Ministério das Minas e Energia. Brasília.

Rosa, L. P.; Schaeffer, R.; Santos, M. A. 1996. "Emissões de Metano e dióxido de carbono de hidrelétricas comparadas às de termelétricas equivalentes" In *Diagnóstico Ambiental e Energético_das Hidrelétricas na Amazônia*. Cadernos de Energia. Edição Especial do Centro de Estudos de Energia - ENERGE. Rio de Janeiro. Brasil.

Santi, A. M. M. 1997. *O Emprego de resíduos como combustíveis complementares na produção de cimento, na perspectiva da energia, sociedade e meio ambiente. Estudo de caso: Minas Gerais no_período 1980-1997.* Tese de MSc. Universidade Estadual de Campinas. Campinas, Brasil.

Silva, R. J. 1994. *Análise Energética de Plantas de Produção de Cimento Portland.* Tese de D.Sc. Universidade Estadual de Campinas. Campinas, Brasil.

Silva, R. J.; Nebra S. A. 1993. "O uso eficiente da energia com as novas tecnologias de produção do cimento". In *Anais do VI CBE. I Seminário Latino Americano de Energia*. Rio de Janeiro. Brasil.

Silva, R. J.; Nebra, S. A. 1996. *Thermoeconomic comparative analysis of different process of cement production*. In *Proceedings of ECOS'96. Efficiency, Costs, Optimization, Simulation and Environmental aspects of Energy Systems.* Royal Institute of Technology. Stockholm, Sweden.

[SNIC] Sindicato Nacional da Indústria do Cimento.1995 and 1996. *Relatório Anual do Sindicato Nacional da Indústria de Cimento.* Rio de Janeiro. Brasil.

Soares, J. B. 1998. *Potencial de conservação de energia e de mitigação das emissões de gases de efeito_estufa para a indústria brasileira de cimento portland até 2015*. Tese de MSc. Universidade Federal do Rio de Janeiro. Rio de Janeiro, Brasil.

Tolmasquim, M. T.; Szklo, A. S. coords. 1999 (in press). *A energia no Brasil na virada do milênio – A matriz energética do Brasil*: 1998-2010. Rio de Janeiro. Brasil.

[WEC] World Energy Council. 1995. *Energy efficiency improvement utilising high energy. An assessment of energy use in industry and buildings.* Report & Case Studies. pp. 143-151. United Kingdom.