Reduction of CO_2 Emissions from Cement Plants

by

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

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Governments around the world have been pressured by society to discuss environmental issues, and global warming is one of the most controversial debates. The Kyoto Protocol is an agreement made under the United Nations Framework Convention on Climate Change (UNFCCC). Under Kyoto protocol some countries committed to reduce their Greenhouse Gas (GHG) emissions. The Intergovernmental Panel on Climate Change (IPCC) has predicted global rise in temperature and carbon dioxide is a major greenhouse gas responsible for global warming. The cement industry contributes approximately five per cent of the total CO_2 emitted worldwide.

Currently Canada sustains a very aggressive objective to reduce GHG emissions to support the Kyoto Protocol. It is clear that international affairs and global polices will affect different sectors and even though cement production and distribution is constrained by location and natural resource availability, the major cement producers around the globe will be required to meet more stringent environmental regulations.

Kyoto presents a 'cap and trade' mechanism that requires countries to reduce, on average, 5.2 per cent below their 1990 baseline. This reduction must take place between 2008 and 2012. Although these caps are country specific, most countries are requiring industries to have particular objectives for reduction. This can be seen especially in European countries.

The credit trade opportunity increases the possibility for an economical justification of new and environmentally friendly solution for GHG emissions abatement.

St Marys Plant, located in St Marys, Ontario, was used as a case study to evaluate the results of various modifications on cement plants operation that can impact on the plant CO_2 emissions. An economic model which objective is to highlight the best selection strategy to reduce CO_2 emissions with the least cost was developed using St Marys Plant data as part of this thesis.

St Marys Plant achieved a significant result of 23.6 per cent reduction in CO_2 emissions per tonne of cement produced. The results were achieved mainly by applying a progressive approach prioritising project implementation effort and feasibility.

St Marys main steps were 1) implementation of a more robust maintenance system, 2) plant optimization and Kiln expert system; 3) alternative fuels and 4) major equipment modifications.

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Table of Contents

List of Tables

List of Figures

Nomenclature

AASHTO - American Association of State Highway and Transportation Officials

C3A - tricalcium aluminate

C4AF - tetracalcium aluminoferrite

C3S - tricalcium silicate

CKD - cement Kiln dust

GHG - greenhouse gas

LOI - loss of ignition

SLC - St Lawrence Cement

SMC - St Marys Cement Plant

S/R - silica ratio

WDF - Waste-Derived Fuel

WRI - World Resource Institute

WBCSD - World Business Council for Sustainable Development

Chemical Symbols and Formulae

Al_2O_3 - aluminium oxide

C - carbon

$CaCO_3$ - calcium carbonate

CaO - calcium oxide

3CaO.SiO - tricalcium silicate

CO - carbon monoxide

CO_2 - carbon dioxide

$3CaO.Al_2O_3$ - tricalcium aluminate

$4CaO.Al_2O_3.Fe_2O_3$ - tetracalcium aluminoferrite

Fe_2O_3 - ferric oxide

H - hydrogen

H_2 - molecular hydrogen

H_2O - water

K_2O - potassium oxide

MgO - magnesium oxide

$MgCO_3$ - magnesium carbonate

N_2O - nitrous oxide

Na_2O - Sodium Oxide

NaOH - sodium hydroxide

NO - nitrogen oxide

NO_2 - nitrogen dioxide

NOx - nitrogen oxides

O_2 - molecular oxygen

S - sulphur

SO_2 - sulphur dioxide

SOx - sulphur oxides

SiO_2 - silicon dioxide

Chapter 1: Introduction, Background and Objectives

The rapid deterioration of global environmental conditions indicated to society the increasing necessity to react to and debate environmental issues. One of the most important and debated issues is the enhanced greenhouse effect. The burning of fossil fuels releases more than six billion tonnes of carbon dioxide (CO_2) into the atmosphere each year (The Economist, 2004).

The cement industry plays a significant role in this scenario. Concrete is the world's most important construction material, and for each tonne of Portland cement (an essential component of concrete) produced, approximately one tonne of CO_2 is emitted to the atmosphere. (Natural Resources Canada Climate Change, 2006). According to the International Energy Authority World Energy Outlook 1995, worldwide cement production was responsible for seven per cent of the total CO_2 emitted around the world (Malhotra, 1999). Environmental polices around the world are affecting different industrial sectors and will inevitably affect the cement industry. During the past 10 years, cement industries have been challenged to reduce and effectively control CO_2 emissions. Various international initiatives can illustrate these new circumstances:

- the Greenhouse Gas Protocol initiative developed by World Resources,
- World Resource Institute (WRI) and World Business Council for Sustainable Development (WBCSD) and
- the Kyoto Protocol.

Environmental issues, mainly greenhouse gas mitigation, will have an economic impact on the cement industry. Today, there are some economically acceptable alternatives for manufacturing an environmentally-friendly Portland cement, e.g. substitute materials and alternatives fuels. Whatever alternatives are implemented, they must be pragmatic.

The possibility of making a profit with CO_2 emissions is also a parameter that may impact the competitiveness of cement groups.

The Kyoto Protocol opened for international support on December 11, 1997 at Kyoto, Japan. The main objective of the Kyoto Protocol is to stabilize the greenhouse gas concentrations in the atmosphere, by bringing them to a level that will not interfere with the climate system. The Kyoto Protocol represents an agreement between industrialized countries to reduce their greenhouse gas emissions 5.2 per cent compared to 1990. National targets vary from eight per cent reductions for the European Union and other countries, to six per cent for Canada and Japan. Canada ratified the treaty on December 17, 2002 despite considerable opposition particularly by some business groups and non-governmental climate scientists. In addition, there is also the fear that since U.S. companies will not be affected by the Kyoto Protocol, Canadian companies will be at a disadvantage in terms of trade.

Since the Kyoto Protocol signing, different organizations have developed Measurement Protocols. These protocols have been developed by the organizations partly as a tool for their own GHG Emission Reduction Programs. Presently, the cement sector has followed the WRI and WBCSD GHG Protocol (WBCSD website December 2006).

The objective of this study is to evaluate the impact on CO_2 mitigation by different projects implemented at St Marys Cement Plant., located in St Marys, Ontario, Canada, as well as discussing future steps for CO_2 emission mitigation. The next Chapter will discuss the cement manufacturing process, its energy use, CO_2 emissions and alternatives to improve production.

Chapter 3 will present the results achieved by St Marys Plant from 2000 to 2006 including management system changes as well as major process changes. An economic model that determines the best selection strategy with the least cost with the objective to minimize the total control cost is discussed in Chapter 4. Chapter 5 concludes and put in to perspective the practical results from St. Marys Plant.

Chapter 2: Background and Literature Survey

2.1. Introduction

This Chapter discusses the cement manufacturing process, its energy use, CO_2 emissions and alternatives to improve production. The cement industry is a significant player in the greenhouse gas scenario. Concrete is one of the world's most important construction material, and for each tonne of Portland cement produced, approximately one tonne of CO_2 is emitted to the atmosphere. This scenario raises the necessity of practical solutions and improvements in the cement industry that could result in lower CO_2 emission.

2.2 Cement Manufacturing Process

Portland cement manufacturing requires a precise mix of raw materials. This mix is commonly called the raw mix and consists of two main natural raw materials: limestone (calcium carbonate-$CaCO_3$) and argillaceous materials (alluminosilicates). The cement industry must therefore start by quarrying limestone and clay.

The main objective of raw material control is to produce a Kiln feed that will allow the production of a quality cement clinker, while conserving as much energy as possible. The cement clinker (clinker) requires a defined proportion of the elements calcium, silicon, aluminium and iron; all these raw materials together with the fuel ash must combine and form the typical clinker composition: $CaO = 65 \pm 3\%$, $SiO_2 = 21 \pm 2\%$, $Al_2O_3 = 5 \pm 1.5\%$, and $FeO_3 = 3 \pm 1\%$ (Bhatty 2005).

The main process steps will be discussed next; Figure 1 shows the main unit operations in the cement process.

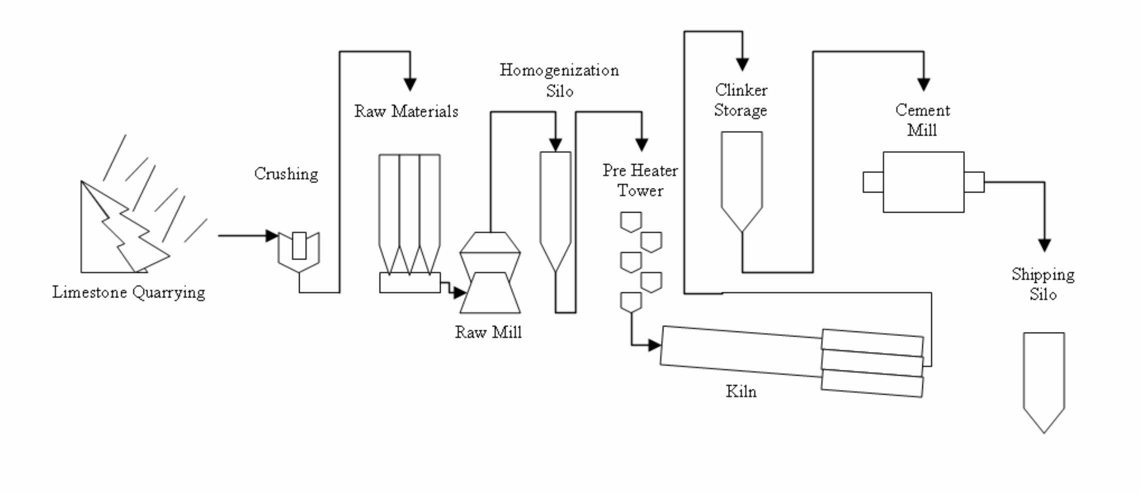


Figure 1: General Cement Process Diagram

2.2.1 Limestone Quarrying and Crushing

Limestone is the most suitable source of $CaCO_3$ for cement production. Other raw materials are silica, alumina, and iron. Raw Feed consists basically of limestone; the typical limestone used in cement production has 75 to 90 per cent $CaCO_3$. The reminder is magnesium carbonate ($MgCO_3$) and impurities.

Typically, cement plants are located close to the limestone source. The quarrying operations are done using the open mining process. Quarrying is done through drilling, blasting and using heavy earth moving equipment such as bulldozers and dump trucks. The quarried raw material is then transported to the cement plant using mechanical conveying equipment, such as conveyor belts. The main steps to produce crushed limestone are:

- Overburden removal – remove soil, clay, and loose material and vegetation;
- Blasting of the limestone deposit;
- Transport of the blasted limestone to the Primary Crusher; and,
- Crushing of the limestone at the Primary Crusher to reduce stone size to about 25 cm and then through the Secondary Crusher to reduce stones to approximate size of 5 to 10 cm).

The quarried limestone is normally in the form of large boulders, ranging from a few centimetres inches to several meters in diameter. These varying sizes of limestone need to be crushed to about 4 cm in order to be used in the next step for the raw feed preparation. Limestone quarrying will consume approximately 85 per cent of the total energy used in the mining process. The other 15 per cent will be consumed by the crushing process and the limestone transport system composed of a sequence of conveyor belts and dust collectors.

2.2.2 Additives Storage Hopper

To achieve the required raw feed composition it is necessary to add some iron, bauxite, quartzite and/or silica. These materials can be stored in silos or hoppers and are transported using conveyor belts in conjunction with weigh-feeders. These additives provide the cement plant with the flexibility to correct any natural deviation in the raw materials composition.

2.2.3 Raw Mill

The raw material mix will be ground up before being sent to the process stage. The grinding process can be performed using either ball mills or vertical roller mills. During this stage, part of the excess heat from the Kiln is used to dry the raw mix.

2.2.4 Blending and Storage Silo

To reduce the natural chemical variation in the various raw material sources it is necessary to blend and homogenize the raw material efficiently. The main objective of this step is to minimize impacts on the efficiency of the Kiln.

2.2.5 Preheater and Kiln

The main step in the dry cement manufacturing process is the raw material burning or clinkering. This step takes place in the Preheater Tower and in the Kiln. The Preheater Tower is composed of a series of countercurrent flow cyclones that transfer heat from the Kiln to the raw materials. Some of the newest Preheater Towers have a section which contains a fuel combustion chamber shown in Figure 2. This section is commonly called precalciner due to its function. In this stage the calcination of the raw materials will start and CO_2 will be formed.

The Kiln is the main piece of equipment in the cement plant and “are the world’s largest piece of moving industrial process equipment and one of the hottest” (Choate 2003). The kiln is a long, horizontal, rotating, cylindrical pipe that is at least 60 m long and can be up to 200 m long and with diameters ranging from 3 to 9 m. Its internal surface is covered with refractory bricks (Duda 1977).

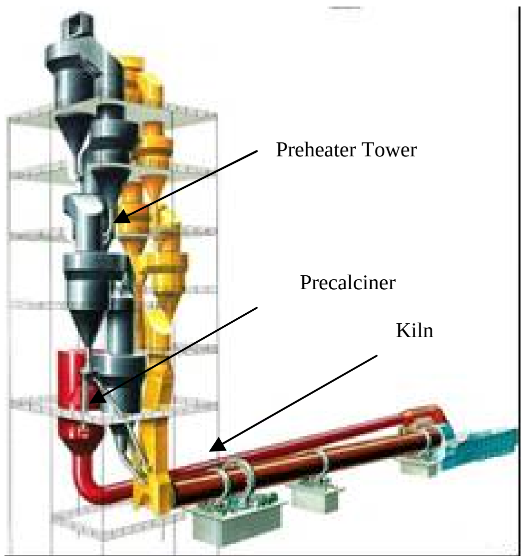


Figure 2: Preheater Tower and Precalciner (Votorantim 2001)

Blended raw materials are fed in to the upper end of the Preheater Tower going all the way through the end of the rotary Kiln. The Kiln slowly rotates, approximately one to four revolutions per minute, and the raw material tumbles through increasingly hotter zones. At this point the sequence of chemical and physical changes will start to take place as the temperature increases. The flame can be fuelled by powdered materials such as coal, petroleum coke, or by natural gas, oil, and recycled materials. The heat will start a series of chemical reactions and the raw material becomes molten, and fuses together into modules, called clinker, are the final product from the Kiln. The clinker is discharged red-hot from the end of the Kiln and conducted through different types of coolers to partially recover the thermal energy and lower the clinker handling temperature. Kilns are classified into two groups:

- Dry Kilns- a newer and more energy efficient process; and,
- Wet Kilns- old technology where nearly 30 to 40 per cent of the thermal energy is used to evaporate the raw material moisture (Choate 2003).

Wet Kiln technology replaces the Dry Kiln technology. Figure 3 shows a considerable number of Wet Kilns replaced by Dry Kilns or decommissioned in U.S in the last 20 years.

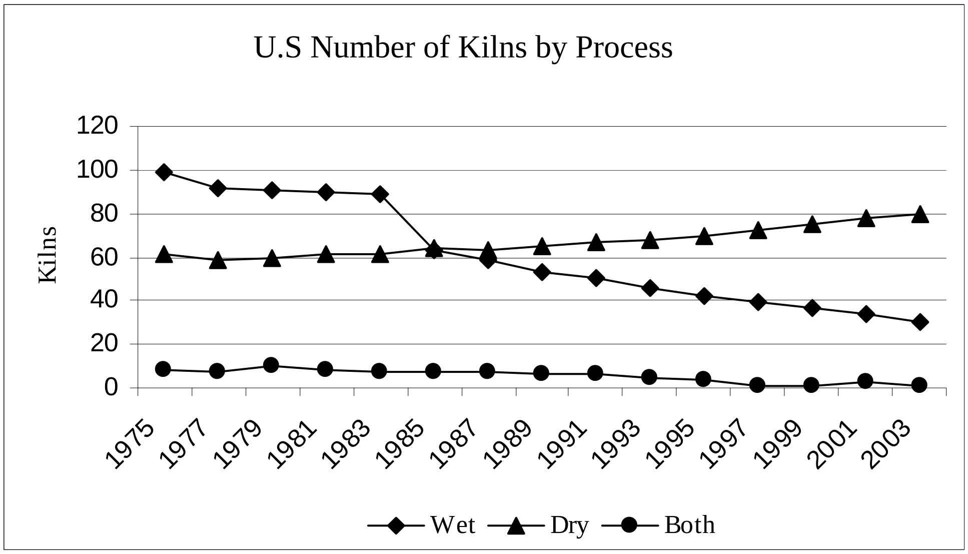


Figure 3: Number of Kilns by Process in the United States (Sullivan 2001)

The raw material will pass through a series of chemical reactions until the clinker formation. Table 1 describes the sequence of chemical and physical changes that take place in the Preheater tower and inside the Kiln (Choate 2003).

Table 1: Sequence of Chemical and Physical Changes in the Preheater Tower and Kiln.

Temp. °C	Process Description	Chemical Reaction
HEATING PROCESS		
< 200	Water evaporation	-
>500	Decomposition of mineral structures and oxide formations	$Al_2O_3.Fe_2O_3 = Al_2O_3 + Fe_2O_3$ $Al_2O_3.SiO_2 = Al_2O_3 + SiO_2$
>800	Belite formation	$CaO + SiO_2 = CaO.SiO_2$ $CaO.SiO_2 + CaO = 2CaO.SiO_2$ $CaO + Al_2O_3 = CaO.Al_2O_3 CaO.Al_2O_3 + 2CaO = 3CaO.Al_2O_3$ (C3A) $CaO.Al_2O_3 + 3CaO + Fe_2O_3 = 4CaO.Al_2O_3.Fe_2O_3$(C4AF)
800-900	**Limestone calcination**	$\mathbf{CaCO_3 = CaO + CO_2}$
>1260	Liquid phase formation	
≈ 1450	Aluminate formation	$2CaO.SiO_2 + CaO = 3CaO.SiO$
COOLING PROCESS		
1300-240	Cooling and crystal phase formation	-

2.2.6 Cooler

The clinker coming out of the Kiln is approximately 1500ºC. It is cooled in an air-cooled cooler. Ambient air is blown into the cooler to exchange heat between the hot clinker and the ambient air. After cooling the clinker temperature drops to approximately 170ºC.

2.2.7 Coal Mill

The coal mill is a ball mill that uses fuel such as coal, coke or grinded pet coke. Inside the ball mills, various sizes of balls are used. Impact and attrition are the principles for grinding the raw material. Larger sized balls are utilized for impact grinding and the smaller balls for attrition.

2.2.8 Cement Mill

The final step to produce cement is the cement grinding, where the clinker is ground together with additives in a cement mill. The cement mill is a horizontal metallic cylinder containing metallic balls. As it rotates the crushing action of the balls grinds and mixes the clinker and additives, forming the final product (Galvao 1996).

2.3 Energy Use in the Cement Manufacturing Process

Portland cement production is a high energy demand process. The U.S. average Kiln fuel energy consumption in 1973 was 7GJ/t. In the mid 1990s it was about 25 per cent above what the best available technology would require, which was about 3GJ/t (Choate 2003).

The main reason for the energy consumption reduction is the conversion from the wet process to the dry process. Dry Kilns require more electricity to operate new equipment such as fans and blowers. However, the new dry process requires less energy overall. The energy used for cement manufacturing is distributed as follows:

- 92.7% Pyroprocessing;
- 5.4% Finishing Grinding;
- 1.9% Raw Grinding (Choate 2003).

Cement Kilns use a large variety of fuel sources to provide the energy required to produce the high temperatures necessary for the clinker formation. Fuel is fed into the rotary Kiln mainly on the back end and raw material flows counter-current to a stream of hot gases. The energy generated by the fuel combustion will evaporate any water from the raw materials, calcine the limestone and finally, form the clinker. Calcination will take place between 700ºC and 900ºC and the clinker formation will occur at approximately 1500ºC.

Carbon dioxide, formed during the pyroprocessing, is a direct consequence of the type of fuel used. The most common fuel sources for the cement industry are:

- Coal;
- Fuel oil; and,
- Petroleum coke.

In addition, some cement plants use natural gas, and alternative fuels. The most frequently used fuels and their energy content are shown in Table 2.

Table 2: Typical Data on Energy Content and CO_2 Emission for Frequent Fuels (Choate 2003).

Fuel	**Energy content (MJ/kg)**	**CO_2 emission factor (kg/MJ)**
Coal	32	0.103
Fuel oil	40	0.077
Natural gas	36	0.056
Petroleum coke	34	0.073 to 0.095

The amount of CO_2 generated by waste fuel is considered to be zero as show in Table 3. This is based on the argument that the CO_2 generated by waste fuels would be released into the atmosphere by natural degradation, and during the natural process the energy content would not be applied in any manufacturing process. In addition, by replacing fossil fuels with waste fuel, cement companies will avoid (by the pyroprocess) extra generation of CO_2. At this time, no consideration is given to CO_2 generated through transportation and the blending of waste fuel.

Table 3: Typical Data on Energy Content and CO_2 Emission for Waste Fuels (Choate 2003).

Fuel	**Energy content (MJ/kg)**	**CO_2 emission factor (kg/MJ)**
Scrap tires	21	NA
Plastics	33	NA
Waste oil	38	NA
Paper residues	6	NA
Waste solvents	18-23	NA

An important point to be considered for any fuel used the cement industry is that the average calorific value for clinkerisation is about 15 MJ/kg and the minimum value to self-support the burner flame is 10 MJ/kg.

Canadian fuel usage (Table 4) is still basically focused on coal with a small percentage of Canadian plants using waste materials (Sullivan 2001). Alternate fuels are used as secondary fuel source based on cost and availability.

Table 4: Canadian Fuel Usage Summary

Type of Fuel	Number of Plants	Clinker Capacity (100 tonnes)	Percent of the Total Capacity
PRIMARY FUEL			
Coal, Coke	6	5718	36.1%
Coal	5	5328	33.6%
Natural gas	2	2160	13.6%
Coke, Waste	1	970	6.1%
Oil, Natural Gas, Coke	1	929	5.9%
Coke	1	732	4.6%
TOTAL	16	15837	100.0%
ALTERNATE FUEL			
Natural gas	5	3821	38.2%
Waste	4	3463	34.6%
Oil, Natural Gas, Waste	2	1989	19.9%
Coal	1	732	7.3%
TOTAL	12	10005	100.0%

In addition, U.S. plants (Table 5) have a much more diversified fuel mix than Canadian plants. It is evident that U.S. plants are more flexible than Canadian plants in their use of different types of fuel and waste fuels (Figure 4). This is basically related to local regulations and fuel availability.

Table 5: U.S. Fuel Usage Summary (Sullivan 2001)

Type of Fuel	Number of Plants	Clinker Capacity (1000 tonnes)	Percent of Total Capacity
PRIMARY FUEL			
Coal	64	54,539	61.1%
Coal, Coke	15	11,217	12.6%
Coke	7	4,831	5.4%
Coal, Natural gas	5	6,748	7.6%
Coal, Natural gas, Coke	3	1,709	1.9%
Coal Oil, Coke	2	2,112	2.4%
Coal, Natural Gas, Coke, Waste	2	967	1.1%

Table 5 Continued

Waste	2	877	1.0%
Coal, Waste	1	2,536	2.8%
Coal, Oil, Natural Gas	1	1004	1.1%
Natural Gas, Coke	1	868	1.0%
Coal, Coke, Waste	1	680	0.8%
Coal, Natural Gas, Waste	1	549	0.6%
Oil	1	402	0.5%
Oil, Coke, waste	1	110	0.1%
Coke	1	96	0.1%
TOTAL	108	89,245	100.0%
ALTERNATE FUEL			
Waste	22	19,165	25.1%
Natural Gas	19	12,984	17.0%
Natural Gas, Waste	17	14,695	19.2%
Oil	10	8,698	11.4%
Coke	9	8,163	10.7%
Natural Gas, Coke, Waste	4	3,530	4.6%
60 Natural Gas, Coke	3	2,877	3.8%
Oil, Waste	3	1,449	1.9%
Coke, Waste	2	1,844	2.4%
Oil, Natural Gas, Coke	1	1,231	1.6%
Coal	1	565	0.7%
Coal, Coke	1	472	0.6%
Coal, Natural Gas, Coke	1	389	0.5%
Coal, Natural Gas	1	308	0.4%
TOTAL	94	76,370	100.0%

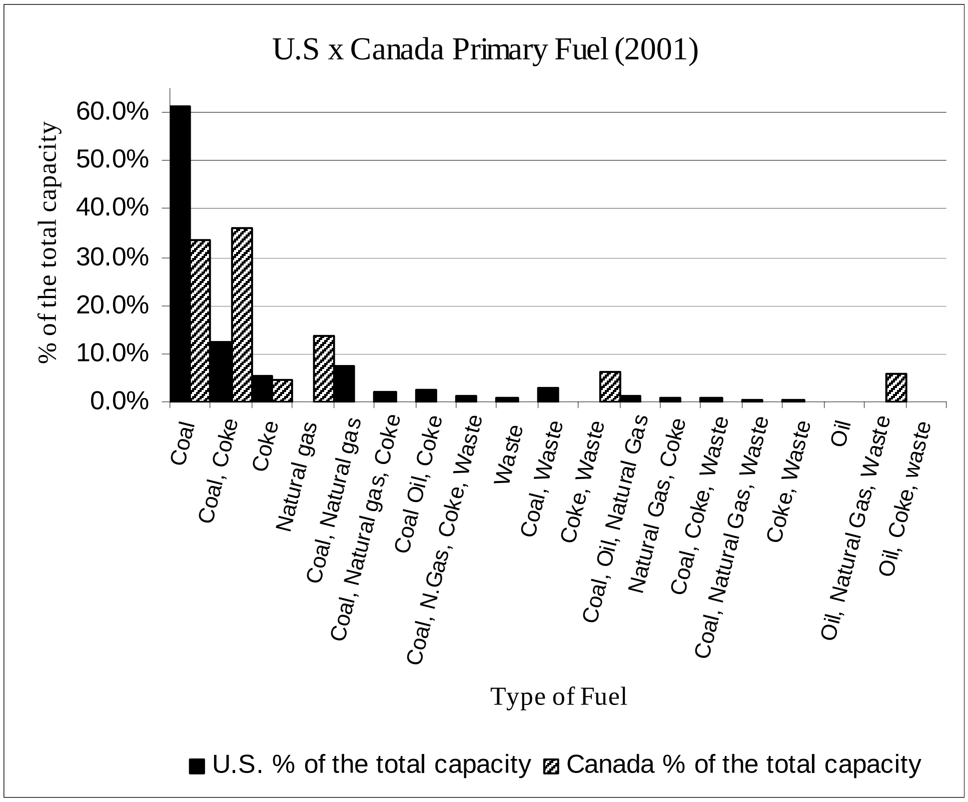


Figure 4: Primary Fuel's Used in Canada and the United States

2.4 Carbon Dioxide Emissions

The main sources of carbon dioxide in cement manufacturing are:

- Combustion of fossil fuel and;
- Limestone calcinations.

Other sources, such as the electricity (as in the case of Ontario, where electricity is partly generated from fossil fuels) and mobile equipment, represent a small contribution to the total CO_2 generated by the cement manufacturing and will therefore not be accounted for in the present study. Approximately, half of the CO_2 emitted by the cement industry originates from the fuel and half from the calcinations (chemical reaction) that will convert raw materials into clinker.

2.4.1 Carbon Dioxide Emissions from Fuel Use

The cement companies use different sources of fuel. The most common are coal, petroleum coke, fuel oil and natural gas.

Among the elements that make up the cement kiln, fuel carbon and hydrogen are the elements that contribute the most energy during the combustion process. Other elements, such as sulphur and nitrogen oxides, are also present in the combustion process and not only represent a small contribution to the energy process, but also represent a considerable environmental concern.

Currently, the cement industry in North America and Europe bases their fuel choice on three basic points: cost, product quality and environmental impact. The fuel that best fills these three basic requirements will be the preferred choice. It is important to note that factors such as the cost of a new firing system, the amount of storage and local fuel availability will also play a key role in the decision process.

2.4.2 Carbon Dioxide Formed by Calcination

A large percentage of cement plants are located close to their source of calcium oxide. This is an essential requirement since limestone represents about two-thirds of the clinker composition by mass. A typical clinker raw mix is made up of approximately 80 per cent limestone. Table 6 shows typical limestone composition in mass per cent.

Table 6: Typical Limestone Composition (Bhatty 2004)

Elements, as oxides	Pure limestone	Intermediate limestone	Siliceous limestone	Cement rock
SiO_2	0.25	6.83	9.05	13.19
AL_2O_3	0.15	2.67	1.03	4.87
Fe_2O_3	0.13	1.14	0.42	1.75
CaO	55.31	48383	48.83	41.96
MgO	0.4	0.7	0.85	2
SO_3	0.02	0.58	0.52	0.83
Na_2O	0.03	0.09	0.11	0.36
K_2O	0.04	0.3	0.35	0.78
Loss on Ignition, LOI	43.66	38.85	38.76	34.2
Silica Ratio, S/R	0.89	1.78	6.24	1.99

During the clinker process limestone will suffer calcination and CO_2 will be formed. The limestone chemical reaction can be expressed by the equation below:

$CaCO_3 \rightarrow CaO + CO_2$

1 kg   0.56 kg + 0.44 kg

The percentage of calcium oxide (CaO) in clinker is usually between 64 and 67 per cent. The complement comprised of iron oxides, silicon oxides and aluminum oxides. The amount of CO_2 generated by the process varies based on the specific loss of the raw materials (limestone) on ignition.

An example of mass balance for production of one tonne of cement is shown in Figure 5 (IEA Greenhouse Gas R&D 1999).

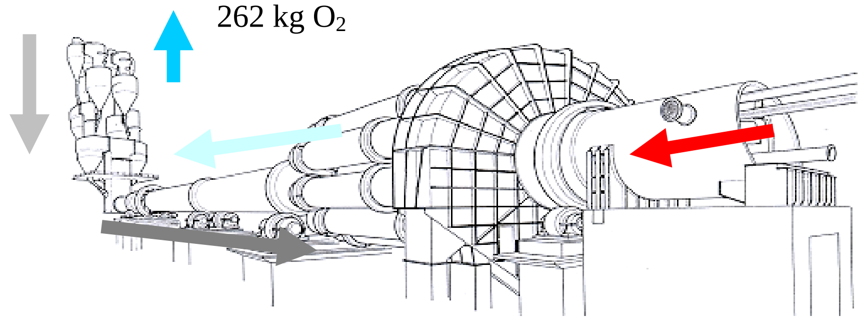


Figure 5: Typical Cement Process Mass Balance

2.5 Alternatives and Improvements for the Clinker Production

GHG mitigation has now become an important factor in creating a sustainable cement industry. Finding alternatives through CO_2 mitigation processes is paramount for the future of the cement industry. GHG emissions are one of the most serious environmental problems that will affect rich as much as poor, developed as much as emerging countries. Although regulated locally by different countries, the top 10 cement producers have their plants spread around the globe, and as part of a sustainability strategy, the cement industry is forced to reduce emissions.

Despite a clear issue and strong arguments the current U.S. administration does not support the Kyoto Protocol. The U.S. position is justified due to potential negative impacts on the U.S. economy.

In addition, GHG mitigation has to overcome commercial and economical barriers. During the last 20 years environmental matters have had more influence in different global agreements; however, since solutions could result in a reduction in the profit margin of certain multinational corporations or adversely impact the economy of industrialized countries, the only possible solution is one that will offer environmental gains and strong business opportunities.

The cement industry plays an important role in supplying one of the most basic materials for virtually all types of infrastructure. This fact brings to the equation the social responsibility involving the cement producer. This social responsibility creates a much deeper discussion than the issues of profits and margins.

It is a fact that 15 to 20 per cent of the world's population consumes large quantities of energy and generates huge amounts of CO_2. This high demand for energy is caused not only by a high standard of living, but also by challenges such as raw material availability, lack of environmental solutions (such as environmentally friendly power plants), and probable shortage of fuel. On the other hand, approximately 80 per cent of the world's population has limited economic resources to solve all serious environmental and social problems. These parts of the world face death, extreme poverty, increasing violence, and do not acknowledge environmental problems.

In order to achieve CO_2 mitigation targets while promoting the sustainability of the cement industry, the following steps have been taken by different cement plants around the world:

2.5.1 Maintenance

Maintenance is one general aspect that involves not only trained personnel, but also the commitment of management to keep and enforce the program principles during the short and long term. Many maintenance programs have been launched with success. One of the most important parts of a maintenance system is preventive maintenance. Preventive maintenance can increase plant efficiency and reduce the cost of corrective maintenance. One example of results delivered by a successful maintenance system is energy savings. Actions such as false air survey and control of the leaking point can significantly increase the kiln thermo efficiency. It is estimated that a simple air leak at the kiln hood can contribute to a 46 kJ/kg of clinker increase on the kiln thermal consumption (IEA Greenhouse Gas R&D 1999).

Other strategies to reduce energy consumption include the gradual substitution of old motors by high-efficiency motors and the implementation of an integrated management system where the daily process routine contributes directly to increase maintenance effectiveness. The feeders and scales performance are examples of equipment that have direct influence on the kiln feed quality. A developed maintenance plan will support the kiln feed quality reducing the deviation on the material proportions which directly affect the fuel consumption.

In general, a good maintenance program will contribute to an increase in the plant utilization ratio reducing the numbers of start-up and kiln preheats during the year (Saxena 1995). Although not easily quantified, it is clear that a well structured maintenance program can highly contribute to emission reduction and plant performance improvement.

2.5.2 Plant Optimization and Kiln Expert System

Plant optimization has been largely implemented in the cement industry not only as an action to reduce emissions, but also to promote higher kiln productivity and runtime. It is common knowledge in cement plants that many minor problems such as kiln seal leaks, cooler inefficiency, fuel atomization or fineness can compromise and impact plant performance. These problems alone can lead to thermal waste of up to six per cent. Air leaks and quality variation on the raw meal composition and fuel fineness have a direct relationship to the feed burnability and air flow through the kiln (Rio Branco 1995).

In addition, as part of the plant optimization the kiln expert system is an automatic kiln control. The expert kiln control system helps the kiln operator to maintain the kiln in the most stable condition possible. The expert system should minimize fuel consumption and maximize clinker production correcting the clinker quality as required. The main idea is to make the process more consistent and reliable. For example, the operator might increase fan speed or reduce fuel injection based on the tower oxygen levels. It is estimated that the kiln expert system can reduce heat consumption by three to five per cent and improve refractory life by 30 to 50 per cent (Votorantim 1994)

2.5.3 Alternative Fuel and Pyroprocessing Improvements

The main opportunities for improvements and reduction of emissions associated with the cement industry are in the pyroprocess. As discussed previously, a large part of energy consumption, and consequently emissions generation, takes place during the burning process. It is estimated that the average pyroprocess efficiency in the U.S. is about 34 per cent. Opportunities for improvement can be found mainly in process upgrades such as replacing wet systems and upgrading preheaters and precalciners. It is important to recognize that new burner designs and fuel systems can also play a considerable part in reducing emissions. New burners and fuel systems can contribute to reduced emissions by improving a cement plants' flexibility to burn alternative fuels, and replacing high fossil carbon fuels with low fossil carbon fuels. An example of fuel substitution is the use of natural gas instead of coal. Some other types of alternative fuels include:

- Gaseous: refinery gases and landfill gas;
- Liquid: mineral oils, distillation residues, hydraulic oil; and,
- Solid: sewage sludge, plastic, tires, petroleum coke and tar.

Alternative fuels can contribute to the cement process not only as an alternative source of energy, but also as a source of raw material. Other impacts of alternative fuel on the plant operation are the refractory utilization rate and preheater tower pressure loss (Grosse 1996). The organic portion will burn and generate energy required for the process. The mineral part will be integrated into the process and will contribute as raw material. Fly-ash is a typical example of alternative raw material that will contribute not only as a raw material but also as an energy source.

During the feasibility study it is important to consider the environmental impacts that alternative fuels may cause. Heavy metals and sulphur dioxide emissions are some of adverse environmental effects that the alternative fuels can cause during the pyroprocess.

Petcoke Substitution

Petcoke is residue from the crude oil refineries. Typically petcoke will present five to 15 per cent volatile. This characteristic will represent a low reactivity and consequently a low burning rate. This will require a finer grinding and burners with higher performance. A second characteristic of petcoke used by the cement industry is the high sulphur content. This substantially increases the sulphur circulation in the kiln and, where combined with a low burning rate, will increase sulphur build-up in the kiln and preheater tower (Roy 2002). The cement industry has a common objective to reduce production cost. One of the partial solutions to reduce cost has been the use of petcoke as the main fuel source. Petcoke has replaced more traditional fuels such as natural gas, coal and oil. The determination to use one fuel over another is usually based on the relative cost of each fuel per unit of heat produced. Petcoke is now 30 to 40 per cent less costly than coal in the Canadian market and is readily available. Some plants, mainly outside of North America, have operated using 100 per cent of petcoke over the past 10 years.

Replacement of Fossil Fuel by Waste-Derived Fuel (WDF)

It is estimated that the use of waste-derived fuel (WDF) will increase by one per cent worldwide per year. The alternative implemented by some cement plants is to use approximately one per cent of WDF to replace fossil fuel (Kihara 1999). It is important to note that this mitigation is indirect, because if these waste products had not been burned in cement kilns, they would have been incinerated or sent to a landfill, generating further CO_2 emissions together with the CO_2 generated by the fossil fuel that was not replaced. This alternative has a potential to add great environmental value by solving the serious problem of waste disposal. Unfortunately, fossil fuel substitution by WDF is not an alternative supported by the general public. The public perception is that it would convert the cement kiln into a simple incinerator. This perception from the public pressures the local authorities to not consider this as a reasonable alternative to reduce fossil fuel consumption.

2.5.4 Raw Materials

Raw Meal Burnability

The contribution of the raw materials burnability is difficult to measure. In general cement plants have targets for production improvement and profit margin when this alternative is considered. Raw materials fineness, composition and chemical module are the main improvements that must be made to achieve a constant raw material burnability. Such improvements could directly impact the amount of fuel used daily by the kiln. These improvements would also extend the refractory life cycle and reduce power consumption (Gouda 1977).

Use of By-products

This alternative can provide a practical solution to the usage of huge amounts of by-products every year, such as fly ash from power plants. In some cases like fly-ash, the by-product can contribute to improve concrete durability. This alternative needs to be studied locally to determine the availability and cost. European countries have been using by-products in high amounts. In general, it is important to note that cement standards need to be reviewed to accommodate the use of by-products as alternatives in the process of reducing GHG emissions (Damtoft 1998).

Replacing Raw Material Limestone by Slag

Blast furnace slag is a non-metallic by-product from the iron production process. Blast furnace slag is comprised of silicates, aluminosilicates, and calcium-alumina-silicates. By replacing raw material limestone with slag it is possible not only to prevent CO_2 emissions due to limestone decomposition, but also to improve raw material burnability. Blast furnace slag is not a new supplementary cementitious material; it has been used by the cement industry as a component blended in cement or as aggregate material in the concrete mixture for the past ten years.

Blast furnace slag incorporation in Portland cement is specified by AASHTO M302 (Collins 1994). Typically there are three types of granulated slag cement that are manufactured:

- Portland cement as covered by AASHTO M85,
- Portland blast furnace slag cement (blended cement type IS); and,
- Slag cement (slag cement type S) as per AASHTO M240

Although blast slag has great use in the cement industry, its use cannot be generalized worldwide, since factors such as the cost of slag and transportation are prohibitive. It is important to observe that only 25 per cent of the energy used to manufacture Portland cement is required. The use of slag has important ecological and economical benefits. For example, the use of slag in Europe has contributed significantly to the efforts to meet the Kyoto targets, and has reduced the energy and raw materials necessary in the cement process (Ehrenberg 2002).

2.5.5 Process Changes

Electrical Energy Savings

Electrical energy is used in the cement plant to drive fans, rotate the kiln and to move materials. In general, the power used in the kiln corresponds to 40 to 50 kWh/tonne clinker. Power savings from the use of high efficiency motors will vary plant by plant and case by case. Most of the motor substitution is done during the replacement period when the motor life is nearly done.

Another energy consumption point in the cement process is the adjustable speed drivers. Drivers are, in most cases, the largest power consumers in the cement process. Adjustable drivers can produce savings from seven to 60 per cent (Choate 2003). These savings will be based on the application and the load applied to the motor and the application in the process.

New Preheater Tower

The preheater tower is a vital part of the process. A group of preheater cyclones should not be considered as individual parts. A new preheater tower with low pressure drop cyclones will reduce the power consumption of the kiln fan system. It is possible to achieve a reduction of 0.6 to 1.1 kW/t depending on the fan efficiency. A new installation can be expensive. In addition, installation and modification are site-specific, which makes it difficult to point out a general return on the investment. A new cyclone system can increase the overall dust transport cost (Jepsen 1998). This indicates that this solution is recommended for dry preheater and precalciner kilns older than 15 years of age.

Kiln Burner

Burner technology has improved quickly. A number of different burners have improved flame control and optimized fuel usage. One of the main objectives of the new burner technology is to create a more stable flame independent of the fuel type. Flame stability is one of the most important factors in maintaining a stable kiln operation. Not only can it cause adverse effects such as kiln refractory damage, but it also represents a safety concern for the plant personnel. An unstable flame will present various ignition points and a variable stand-off distance from the burner tip. In general, kiln burners mix fuel and air by an air stream (secondary air) entrainment into the fuel, and the primary air impulses the fuel. This characteristic will determine the plant's ability to control and stabilize the flame.

The air and fuel mix rate will be determined by the kiln and burner aerodynamics and by the relative momentum of the various jet streams (Greco 1996). The secondary air is limited by the cooler opening and the fuel jet then becomes constrained. If the burner jet momentum is lower than required for a complete mix of fuel and air, a lazy flame will be formed. This will result in high CO and NO_x formation (Johnson 1999). On the other hand if the flame momentum is greater than required it can cause recirculation. The recirculation phenomenon occurs when the excess momentum of the fuel jet is dissipated and exhaust gases from further down the kiln are pulled back into the flame. The recirculation effect has positive effects producing a more stable flame and reducing the effects caused by minor process changes. This also protects refractory from the direct flame attack, improving the refractory life. It is important to note that an extreme high flame momentum and recirculation effect can be harmful to the burner process efficiency, reducing the combustion effectiveness.

2.5.6 CO_2 Capture and Disposal

Different methods for the capture and disposal of CO_2 at the point of combustion have been researched and developed. Examples of possibilities are: chemical stripping, membrane system, cryogenic separation and physical absorption. The implementation cost of each one of these possibilities is highly uncertain; costs are directly related to technical performance, economic growth and fuel type. Moreover, the disposal solutions available today present a great level of doubt regarding the technical feasibility for a full-scale implementation.

The CO_2 concentration in a cement plant is higher than in a power generation process. Studies have shown that the cement production process has a high quantity of low quality heat. This extra heat could be used in the CO_2 capture process. (Thambimuthu 2002)

Chemical scrubbing has been considered as a capture process. Another possibility for the capture process in cement production is oxyfuel combustion, but the effect of higher CO_2 concentration in the flue gas on the clinker quality would need to be better assessed. In general the average cost to capture one tonne of CO_2 is estimated to be around USD 50 (Nazmul 2006).

The different suggested solutions for disposal are: discharge into natural gas reservoirs or aquifers, discharge deep into the ocean or reuse the CO_2 in useful organic compounds. Reviewing all the solutions available today, the ocean scenario has the highest capacity to store CO_2, and absorbs the CO_2 quantities generated by the actual necessity of reduction (Eckaus 1997). It is expected that in the next few years, CO_2 underground storage will be a technical and economical option for CO_2 disposal. Currently, one of the main constraints is the integral long-term immobilisation preventing the CO_2 from migrating and leaking back into the atmosphere. This generates a demand for special “CO_2 cement” similar to the special oil well cement. Unfortunately such cement does not yet exist (ZKG International 2006). Following, is a brief discussion of the most common CO_2 capture methods.

Chemical Absorption:

The chemical stripping method is based on Henry's Law where the absorption depends on the temperature and pressure of the system. Chemical absorption is mainly applicable for a system where the exhaust gases present low concentration of CO_2 and the system pressure is close to atmospheric pressure. The main steps of the stripping method are:

- Absorption of CO_2 by chemical solvents; and,
- Recovery of CO_2 from chemical solvents by using low-grade heat (usually extracted from power plants).

One of the available technologies for removing CO_2 from the gas stream is chemisorption using monoethalnolamine.

The design and costing of CO_2 capture from cement plant flue gas is similar to the design and costing of capturing CO_2 from power plant using monoethalnolamine (Nazmul 2006).

The application of this method for cement plants was considered practicable and, when compared with the same method application on coal and gas power plants it should represent a lower operation cost (Alie 2005). At the St Marys Plant the cost for this method is estimated to be approximately \$49-\$54 per tonne of CO_2 captured (Nazmul 2006).

Physical Adsorption

Physical absorption has its main application with low concentration gases and vapours that are retained in a surface of porous solid materials (such as activated carbon and zeolites). The contaminant, in this case CO_2, is held on the surface of the porous material by (non-chemical) surface forces. The solid adsorbent material is regenerated using heat and the CO_2 capture is complete (Cooper 2002).

Membrane Systems

These gas separation membranes are based on different physical and chemical interactions between the gas stream and the membrane material. Some of the membrane materials currently available are: porous inorganic membranes, palladium membranes, polymeric membranes and zeolites. Two of the membrane types are the gas separation membranes and gas absorption membranes. (Nazmul 2006).

Carbon dioxide capture by a membrane system is not a common approach in the research for CO_2 capture generated by the cement industry. This method consists of a semi-porous structure, through which some chemical species permeate more easily than others. The main obstacle for this technology is the necessity of multiple stages or cycles, which directly increases energy consumption and consequently, cost. (IEA CO_2 sequestration 2006)

Cryogenic Fractionation

The cryogenic fraction method is based on the compression of the gas stream and subsequently, the gas temperature is reduced where the separation is possible by distillation. This method is mainly recommended in cases of high CO_2 concentration (more than 90 per cent). As a down side, this method requires high quantities of energy to compress and refrigerate the gas stream. As an advantage, this method produces liquid $CO_{2,}$ which enables easy transport and storage (Thambimuthu 2002).

2.6 Canada's Leading Producer

St. Lawrence Cement (SLC) is the leading producer of products and services for the Canadian construction industry. The data presented from SLC in this report is from the Joliette Plant in Quebec and the Mississauga Plant in Ontario. Note that the baseline data includes Beauport Plant in Quebec and Northstar Plant in Newfoundland. These last two plants are no longer in operation. SLC's plants in operation today have Environmental Management Systems that are ISO 14001 certified. The Mississauga plant has a production capacity of 1.45 million tones of cement per year and currently employs 200 persons. The Joliette Plant has a production capacity of 1.1 million tones of cement per year, and also employs 200 persons. The company's senior management has a strong commitment to reduce and report GHG emissions, and regularly publishes environmental performance results. The reported data are based on the World Resources Institute and the Cement Working Group of the World Business Council for Sustainable Development (WBCSD) standards for monitoring and reporting CO_2 emissions from the cement sector.

The impressive results achieved by the SLC totalled an 18 per cent reduction in the net specific direct CO_2 emissions from 1990 to 2003. In 1990, SLC emitted, 838 kilograms per tonne of cementations product from four Canadian plants, and in 2003, the net specific direct CO_2 emissions were 638 kilograms per tonne of cementations product from two cement plants. The key projects reported by SLC that were responsible for these significant reductions are:

- The replacement of the less energy efficient kilns at the Mississauga, Beauport and Northstar plants with increased dry diln capacity and increased grinding capacity for GranCem production;
- Cement kiln dust elimination at the Joliette Plant;
- Fuel substitution; replacing conventional fossil fuels with alternative fuels from secondary materials; and,
- Increased use of supplementary materials.

The SLC has a goal to reduce the greenhouse gas emission intensity by 15 per cent from 2000 to 2010. This goal is based on company performance including plants in Canada and United States. The Canadian plant results are important in reaching this goal. Figure 6 and 7 show the specific net CO_2 emissions at Canadian Plants and percentage CO_2 emissions relative to 1990: a considerable reduction of more than 15 per cent since 1990.

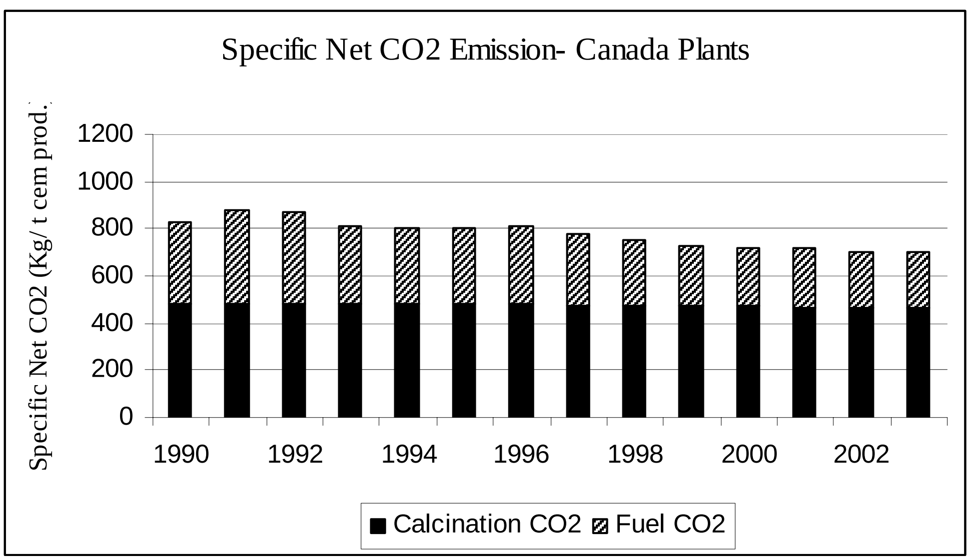


Figure 6: Specific Net CO2 Emissions for SLC Canadian Plants (St. Lawrence Cement Inc. 2006)

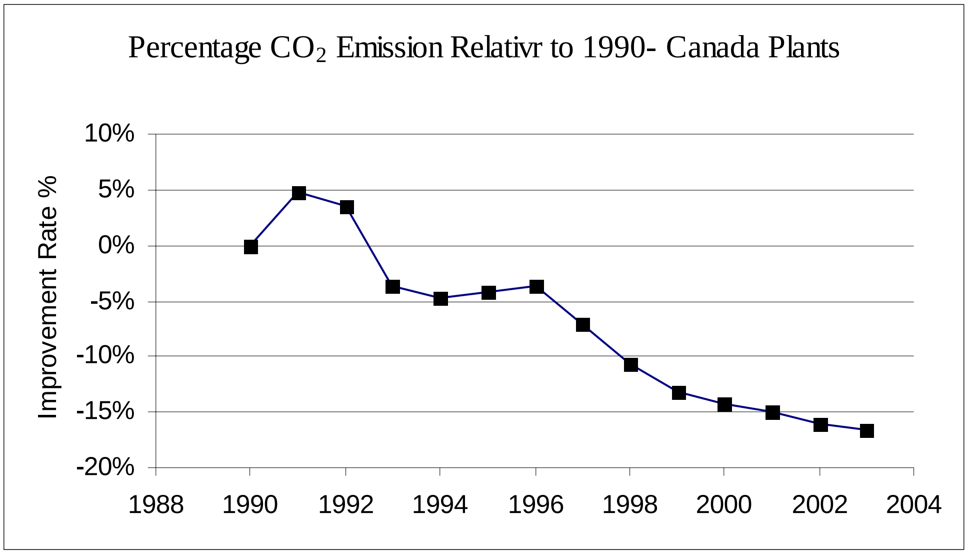


Figure 7: Percentage CO_2 Emissions Relative to 1990 for Canadian Plants (St. Lawrence Cement Inc. 2006)

2.7 Chapter Summary

In this Chapter various alternatives to reduce CO_2 emissions were presented. In general, Cement Plants are taking these alternatives as a valid approach not only to reduce their environmental footprint but also to keep their competitiveness.

Changes from wet process to dry process, alternative fuels and introduction of new raw materials are a natural alternative for the cement industry in North America. Unfortunately, at this point CO_2 capture and disposal is not a practical alternative.

The next Chapter will analyse and discuss several alternatives implemented by St. Marys Plant.

Chapter 3: Analysis and Discussion - *St Marys Cement Plant Results*

3.1 Introduction

Chapter 3 presents the many steps taken by St. Marys Plant to increase the equipment performance, plant management efficiency and to reduce CO_2 emissions.

"St Marys Cement Inc. is a leading manufacturer of cement and construction products in the United States and Canada. St Marys Cement Inc. has its headquarters in Toronto, Ontario, Canada, supplying cementitious materials to the Great Lakes Region and is also an important producer of concrete and aggregates to the Ontario market. St Marys Cement Inc. is a wholly-owned subsidiary of Votorantim Cimentos, an international cement manufacturer based in Sao Paulo, Brazil. St Marys Cement has been contributing to the construction industry around the Great Lakes since 1910. Today the company has manufacturing plants located strategically to serve the Canadian and U.S. markets and has docking facilities in both countries to take advantage of efficient water transportation. Products of St Marys Cement Inc. include cementitious materials from St Marys Cement, ready-mixed concrete and aggregate from St Marys CBM and logistic services from Hutton Transport Ltd." (St Marys Cement Inc. website 2006).

St Marys strategy was to apply a progressive approach prioritising project implementation effort and feasibility.

St Marys main steps were the implementation of a more robust maintenance system, plant optimization and Kiln expert system; alternative fuels and major equipment modifications. These steps and corresponding results are presented below:

3.2 Maintenance System

St Marys' maintenance system has changed in the last five years with the implementation of the Votorantim Cimentos management philosophy. The main point implemented was more professional maintenance planning. A more compressive plan for each kind of maintenance and stops has been implemented. Maintenance cost dropped during the last several years through the coordination of the maintenance schedule and exchange of information and solutions implemented by different plants in North America and Brazil. Maintenance results were able to sustain continuous plant improvement and made it possible to meet a growing cement demand (Figure 8). This is a result of detailed plan that considers the importance and the complexity of the task to be performed and the application of best practices and fundamentals.

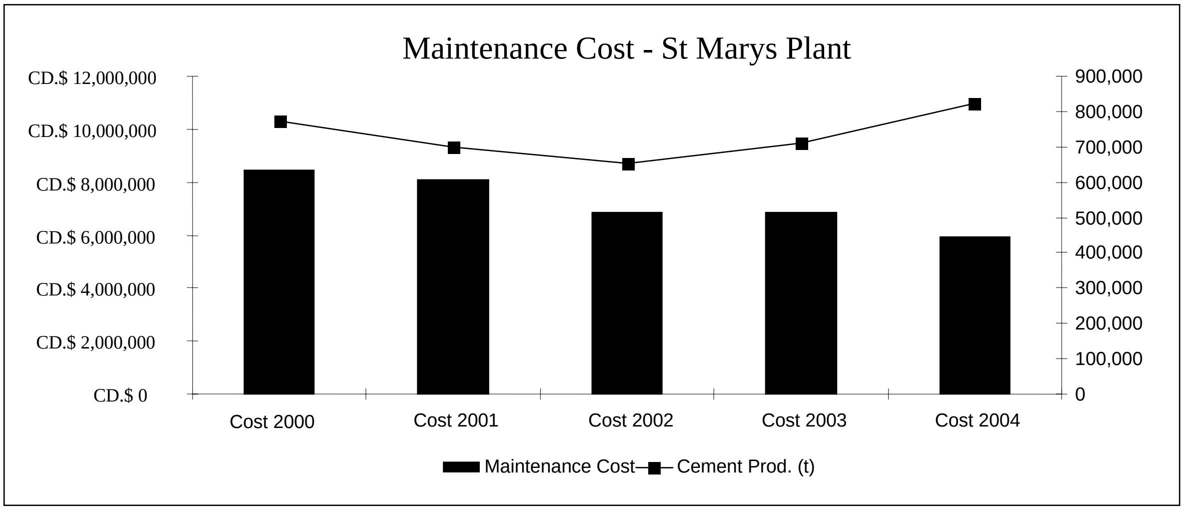


Figure 8: Maintenance Costs for St Marys Plant

3.3 Plant Optimization and Kiln Expert System – LINKMAN

At the St Marys plant LINKman, an expert system manufactured by ABB, was installed in 2002. LINKman's main objective is to stabilize the kiln process reducing fuel consumption, increasing output, and producing a consistent quality. The LINKman system monitors the NO_x, CO and O_2 levels, the temperature at the bottom of the four-stage preheater and the power required to rotate the kiln. The process is optimized by controlling the feed-rate to the kiln, its rotational speed, and the fuel supply. Overall, the plant optimization has supported different process modifications and fuel changes.

Research suggests (Programme IEA Greenhouse Gas R&D 1999) that gains with optimization of process control and management systems typically represent an emission reduction through energy improvements between 2.5 and five per cent. At this moment is not possible to point out how much is the direct contribution of the optimization system over the plant results.

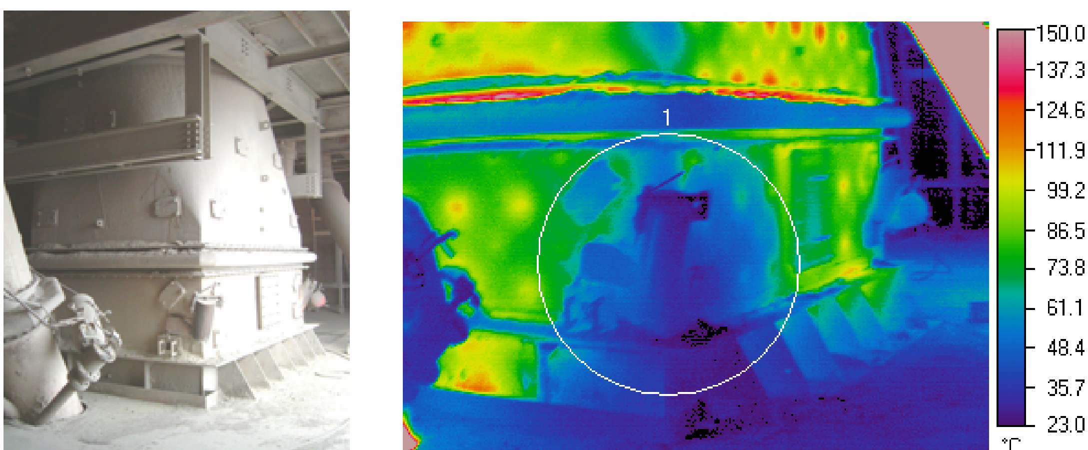
3.4 Alternative Fuel and Pyroprocessing Improvements

Petcoke Substitution

St Marys started to use petcoke as a substitute fuel in 2002. Cost was the main drive to substitute coal with petcoke. Today, the cost of petcoke is approximately 55 per cent of the cost of coal. Petcoke's low volatile percentage represents a challenge regarding its burning rate. A finer grinding is required to achieve a reasonable burner rate. This obstacle reduces the coal mill production requiring a more specific process optimization on the fuel system.

A second obstacle presented by petcoke use is the high sulphur content. This increased sulphur circulation in the Kiln combined with a low burning rate, increased build-up in the kiln and in the preheater tower. One example of new applications used to overcome these difficulties is the thermo survey using an infrared camera (Figure 9). It has proven to be an effective technique to detect obstructions in the preheater tower.

Figure 9 shows the heavy sulphur build up, the temperature change shows the sulphur condensation and the material accumulation reducing the heat exchange and gas flow on that specific point.



	Circle1
Avg °C	48.9
Min °C	19.1
Max °C	87.7
Delta °C	

Figure 9: Preheater Tower Sulphur Build-up

St Marys achieved 100 per cent petcoke substitution in 2006. This required a great effort to overcome all process impacts. Figure 10 shows the petcoke substitution since 1990 and the CO_2 emissions from the fuel component. Even though petcoke has a heat value greater than coal, the total CO_2 emissions are not directly related to the petcoke substitution. During this last five years, St Marys plant has suffered the consequences of the petcoke usage. Tower obstruction and sulphur rings in the kiln directly affected production and kiln run time increasing pre heating and low productivity periods.

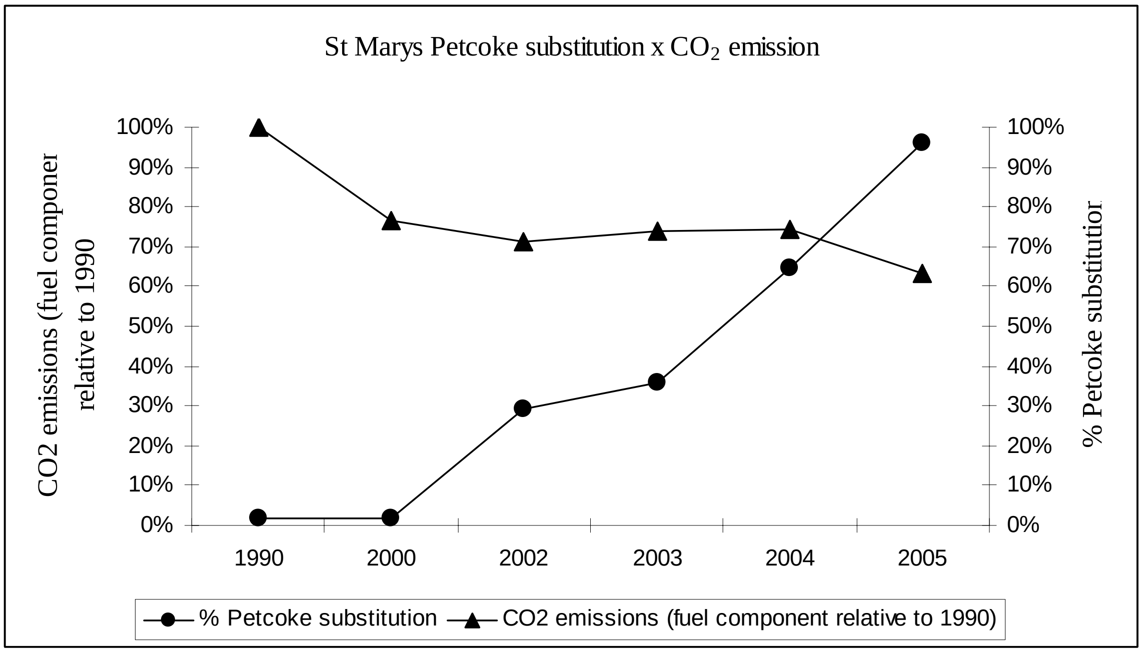


Figure 10: Petcoke Substitution at St Marys Plant

Low NO_x Burner

The fuel system is a key element in rotary kilns. As part of the fuel system the burner is fundamental to optimize the combustion of fuel in the cement kiln. Some of the critical considerations during the design of the burner system are safety, flexible operation, product quality, energy efficiency and environmental impacts. St Marys Plant installed a low NO_x burner manufactured by Unitherm Cemcon on May 7, 2006. The new burner has a multifuel capacity to handle natural gas, heavy oil, pulverized coal, petroleum coke, and solid secondary fuel such as plastic or sewage sludge. The new burner should provide a complete fuel control, directional adjustability, and flame shape control. This will provide the flexibility to burn multiple fuels without compromising environmental performance, while keeping NO_x and CO_2 emissions to a minimum. The new burner simplifies operation, during the preheating period by having a natural gas channel installed in the main burner. One of the most important features of this burner is its simplicity of operation. With more resources to set the flame shape, performance is optimized. As shown in Figure 11 and 12 the adjustable air channel system gives infinitely variable swirling positions making it possible to control the flame shape for different types of fuels. Figure 13 shows different temperature profiles for two different radial air adjustments.

Figure 11: The Burner Pipe New Design:

Figure 12: Unitherm Burner

- Unitherm Cemcon Mono Airduct System (MAS) burner
- The system is capable of injecting three separate and distinct fuels, plus air

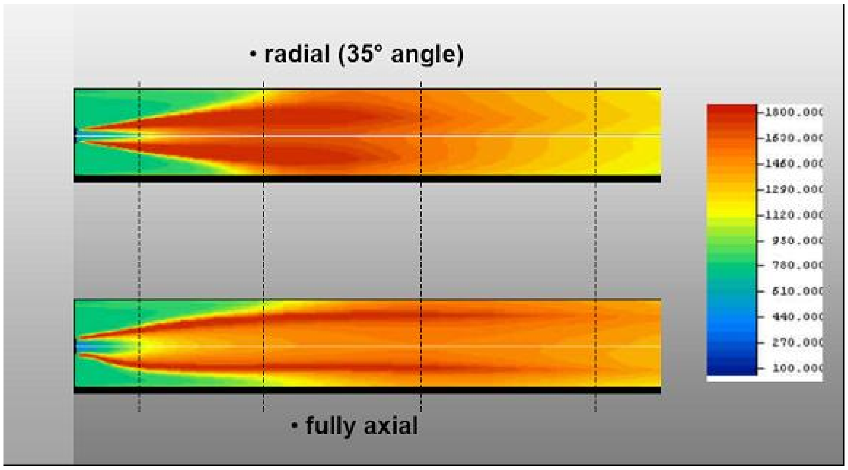


Figure 13: Temperature Profile Different Radial Air Adjustments.

In the first month of operation the new burner produced a substantial reduction in NO_x and CO_2 formation.

3.5 Process Changes

Pre Heater Tower Modification

At St Marys Cement the preheater tower was modified in 2002. The old tower consisted of two streams with four stages. The objective of all modifications made in 2002 was to reduce the specific fuel consumption and increase the heat change and the cyclone efficiency. Figure 14 shows the pressure change after the project and during the fuel substitution process. At the same time, the pressure across the kiln system dropped allowing the specific energy consumption necessary to exhaust the gas from the kiln to drop. The reduction in pressure drop was achieved by installing larger inlet and outlet areas which provided more space for the gas flow in the top part of the cyclone.

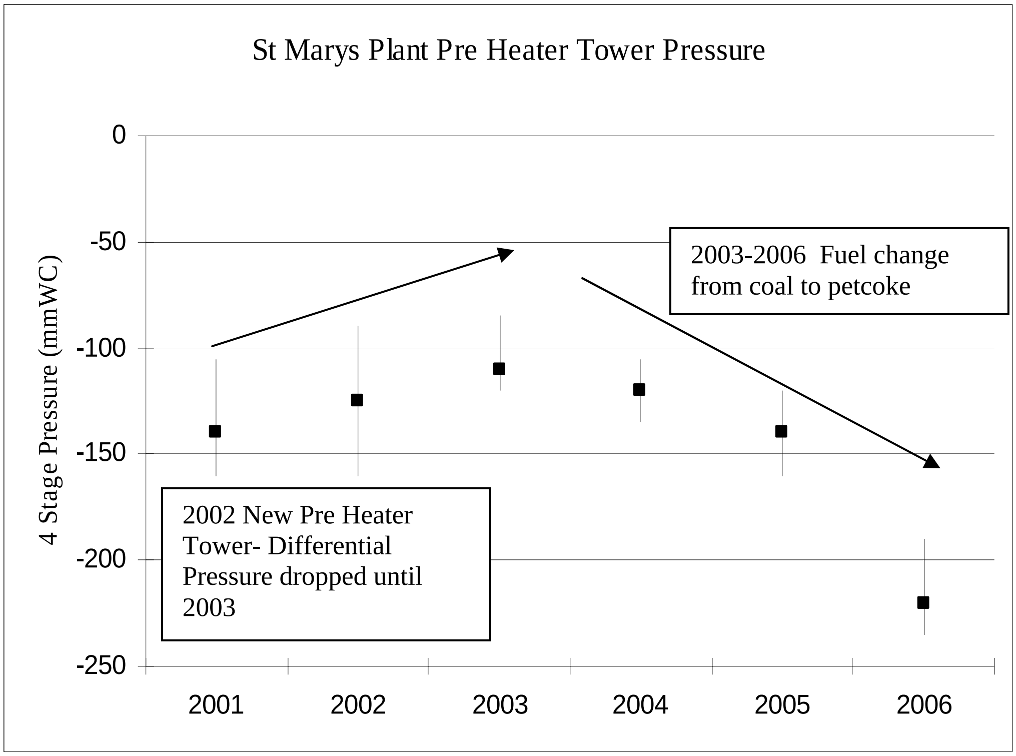


Figure 14: Preheater Tower Pressure at St Marys Plant

Wet System and Clay Mill

Within the process of preparing raw materials for cement manufacture, the primary components are comprised of the following approximate proportions:

Limestone	73 %	Mined on site
Flyash	11 %	By-products delivered in Wet and Dry States
Clay	9 %	Mined on site
Silica	6 %	By-products delivered in Wet and Dry States
Iron	1 %	By-products delivered in Wet States

The raw materials traditionally require pre-processing that allows year round material handling. This is accomplished by pre grinding, drying, and pulverization into segregated storage silos. The flyash, Clay, Silica, and Iron inputs are processed in this fashion by a natural gas fired ball mill system (hence forth known as the Clay Mill).

The Clay Mill system is a large consumer of both natural gas and electrical energy and adds substantial cost to the production of cement clinker. Environmentally, this is the second largest contributor to fugitive dust and GHG output at the facility. This milling system was a traditional fail safe method for preparing raw materials with moisture and variable composition from mined and outdoor storage piles year round. It was identified that sufficient secondary waste heat was available from the kiln line process for raw milling and drying of all raw material inputs in the main vertical roller mill.

The overall technological objective is to develop the knowledge to consistently input raw materials directly from the mine or outdoor storage year round, and bypass the Clay Mill.

Specific objectives are:

- Prepare and store clay from the clay mine for direct feeding via outdoor hopper;
- Develop hopper and feeding technology to be robust for year round operation;
- Extend the system to include by-products of wet silica, iron and flyash; and,
- Find operating parameters that allow use of dry and wet materials in the existing vertical roller mill and computer blending system without affecting output, wear, and reliability.

There were a number of technological advancements that St Marys was seeking to achieve. Specific advancements sought were:

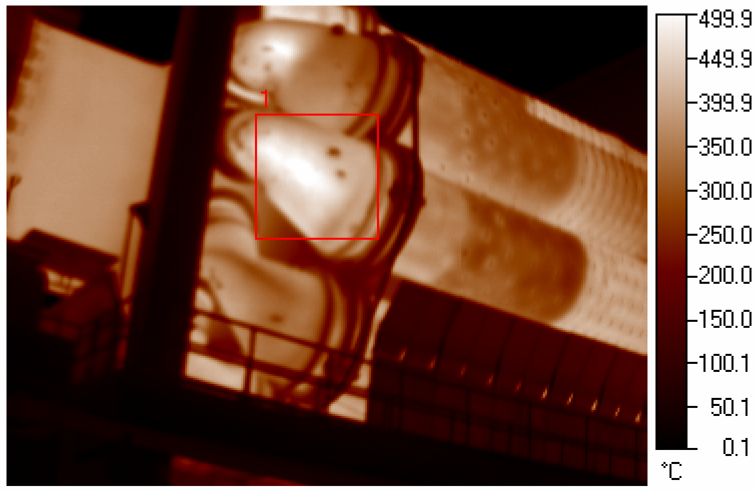
- Eliminate the cost and environmental impacts of the Clay Milling System such as GHG emissions, NO_x and CO_2 directly and indirectly related to the old Clay Mill process;
- Elimination of the fugitive dust generated by the old clay and silica storage piles using a two-dome storage building;
- Reuse secondary process heat;
- Monitor system performance, quality and standard deviation in raw material feed for the kiln system, meeting or exceeding the quality and performance standards for clinker and cement; and,
- Expand the flexibility of current and future raw material used.

A new series of design strategies were studied so that the storage of the materials can be controlled and protected from the elements. The hopper system was enclosed, heated and weather proofed (Figure 15). Research into material handling and systems design continue. The project has successfully operated through the first winter.

Figure 15: Wet System Hoppers at St Marys Plant

Grate Cooler

Grate Coolers are standard technology for any new kiln. Planetary coolers are mainly found in kiln lines installed during the 1970s. St Marys Plant has used planetary coolers since 1977. One of the main issues with the planetary cooler was the excessive number of stops caused by cooler damage, especially at the “elbow” and transition sections. Figure 16 shows a thermo image of one of the coolers and the high heat load that was applied in that section due to the high temperature clinker flow.



St Marys Plant -Cooler 4, point 1 temperatures

Avg °C	390.1
Min °C	151.0
Max °C	510.0

Figure 16: Planetary Coolers at St Marys Plant

Planetary coolers, when compared with the new generation of coolers (grate coolers), have lower energy efficiency and recovery. It is estimated that grate coolers can represent an energy savings (fuel consumption) of up to eight per cent (Nathan 1999). It is expected that the emission reduction should correspondent to the reduction in energy use. In addition, the lower clinker temperature at the exit of the cooler not only conducts less thermal losses, but also improves the clinker crystal formation.

The larger cooler capacity will allow an increase in clinker production and consequently a reduction in the intensity rate of emissions. Figure 17 shows the increase in the daily production average after the grate cooler start up in May 2006.

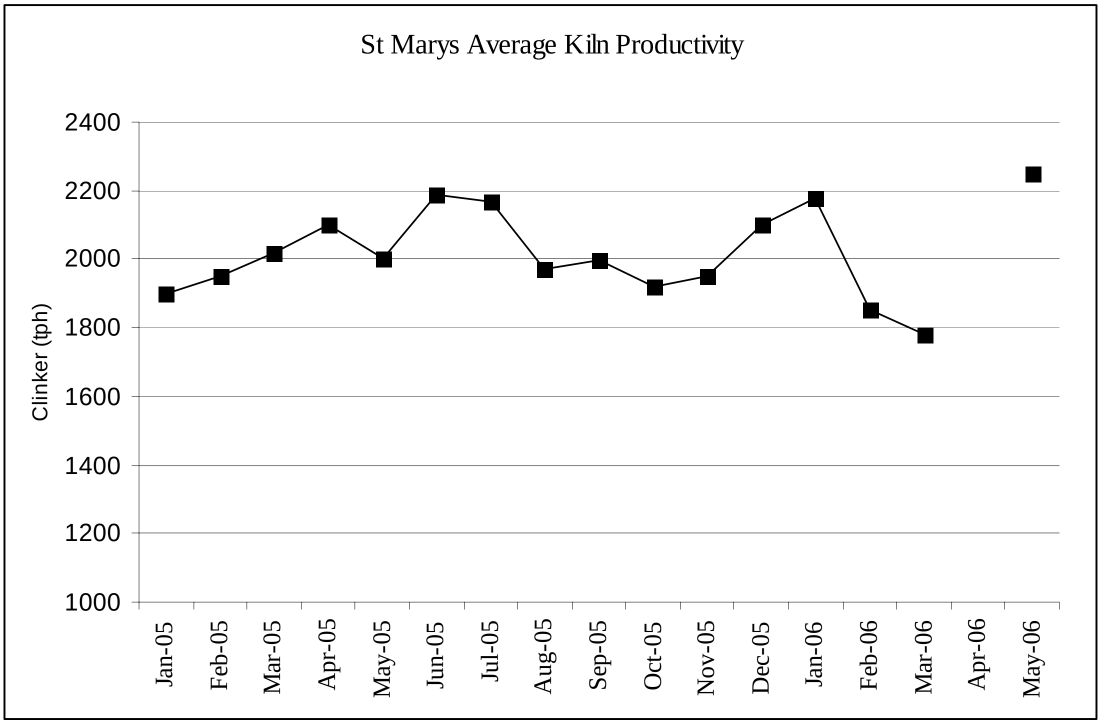


Figure 17: Kiln Productivity at St Marys Plant

As observed previously, the productivity increase should represent a direct emission reduction. In the St Marys case this reduction should be noted as a drop in the emission rate and not in the total emissions due to the substantial increase on clinker production.

3.6 St Marys Overall Results

The St Marys Plant has received numerous process modifications improvements in the last five years (Table 7). All these improvements (Figure 18) have reduced the specific net CO_2 emission since 1990, with the exception of 2003-2004. During this period, the implementation of alternative fuels (fluid coke) resulted in the increase of plant shut downs. This two years represents the Plant adaptation to the implementation of the new fuel and burning process. Overall, the specific net CO_2 emission dropped from 876 kg CO_2 per tonne of cement produced in 1990 to 670 kg of CO_2 per tonne of cement produced in 2005. These alternatives and improvements produced a reduction of 23.55 per cent in the specific net CO_2 emissions.

Table 7: Improvements Chronology at St Marys Plant

Date			Improvements Chronology at St Marys Plant
2000	to	2003	Maintenance system implementation
2002	to	2002	Pre heater Tower modification
2002	to	2003	Linkman
2003	to	2005	Fuel change burning over 90% fluid coke
2005	to	2006	Clay Mill / wet system
2006	to	today	New burner and grate cooler

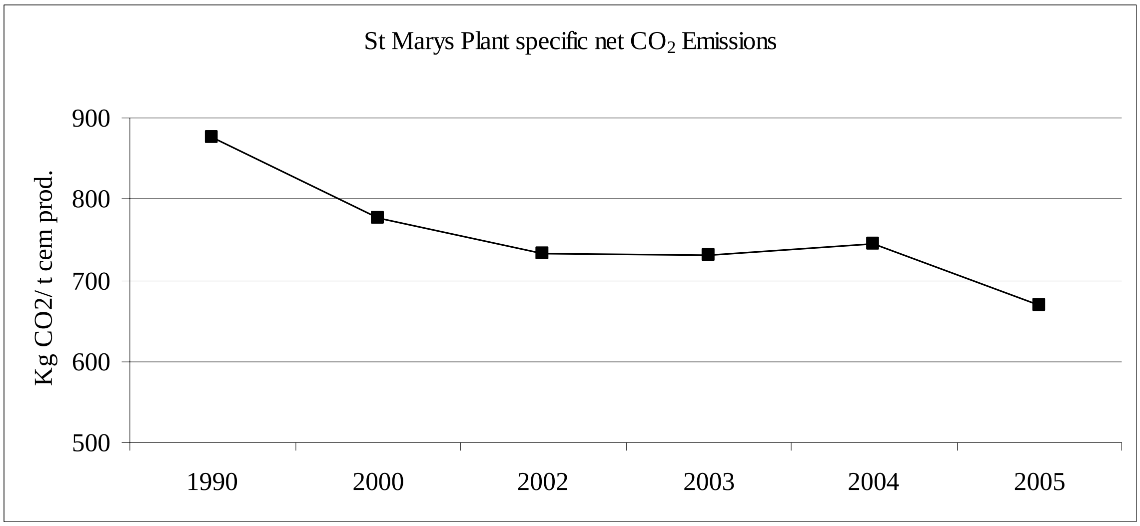


Figure 18: Specific CO_2 Emissions at St Marys Plant

As a down side from the environmental point of view, the total CO_2 emissions from the St Marys Plant has been practically unaffected (Figure 19) because of the increase in cement and clinker production (Figure 20). This is clearly explained by the clinker and cement production increase from 1990 to 2005. Appendix 1 shows in detail the production data and related CO_2 emissions following the WBCSD Working Group Cement CO_2 Emissions Inventory Protocol, in accordance with the Technical Guidance on Reporting Greenhouse Gas Emissions from Government of Canada.

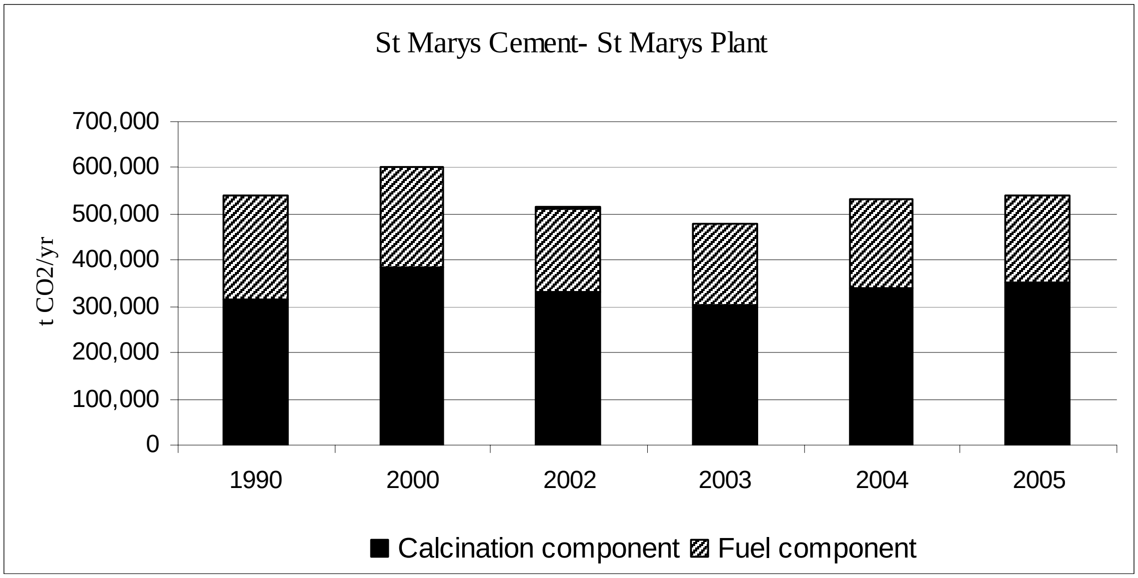


Figure 19: CO_2 Emissions at St Marys Plant

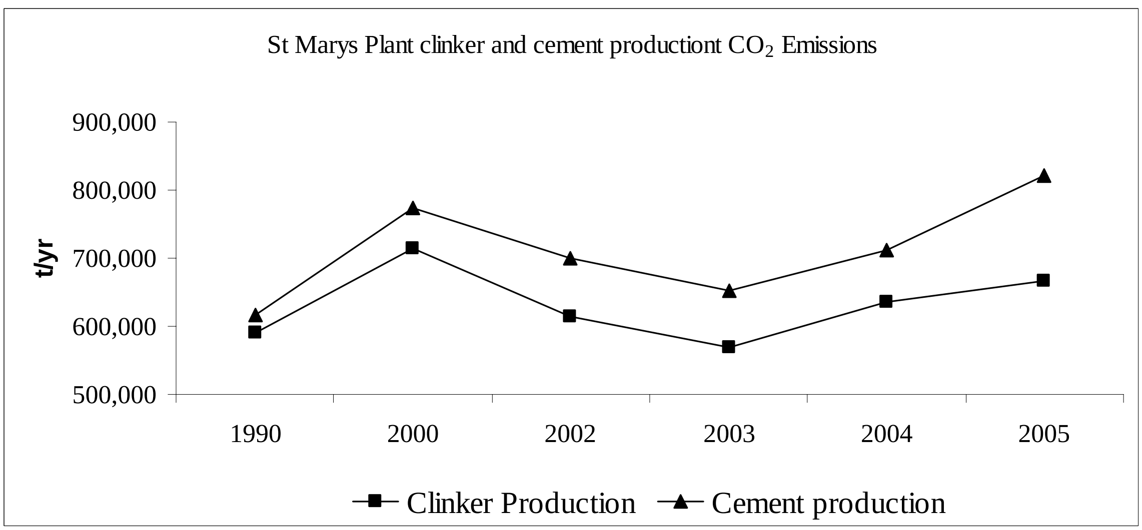


Figure 20: Clinker and Cement Production at St Marys Plant

3.7 Chapter Summary

St. Marys Plant represents a unique case study were several alternatives were implemented during the last 6 years making possible to have a clear view of the impact of every solution in the same system.

In general new technologies will produce a positive environmental impact. The results of new management systems and technologies implementation support the affirmation that a reduction on the CO_2 emissions is possible and reductions over 20% will be an achievable reality for different cement plants.

Chapter 4: Mathematical Model for CO_2 Reduction

4.1. Introduction

An optimization model for the cement industry is formulated in this Chapter. This model will reveal that the effort necessary to implement specific solutions represent a considerable increase on the regular operational cost of the cement plants. The results produced by the model will show that the actions similar to the ones taken by St. Marys Plant described in Chapter 3 can produce results compatible to the theoretical findings.

4.2. Optimization Model

The mathematical model consists of an objective function to be minimized and equality and inequality constraints. The objective of the model is to find the best strategy or mix of strategies to reduce CO_2 up to a certain target with minimum overall cost for cement production while meeting the demand.

The objective function to be minimized can be written as:

$$Z(\$/yr) = \sum_r C_r R_r + \sum_i \sum_f C_{if} P_{if} + \sum_i \sum_f R_{if} X_{if} + \sum_i \sum_e C_{ie} Y_{ie} + \sum_i \sum_c C_{ic} Z_{ic} \quad (1)$$

Where:

Z : annualized capital and operating cost of the cement plant ($/yr)

Cr : cost of purchasing raw material r ($/tonne)

Rr : purchased amount of raw material r (tonne/yr)

Cif : operating cost for a unit i with fuel f ($/tonne)

Pif : amount produced from unit i using fuel f (tonne/yr)

Rif : retrofit cost for switching unit i to run with another fuel f ($/yr)

Xif : binary variable representing switching or not.

Cie : cost of applying efficiency improvement technology (e) on unit i ($/yr)

Yie : binary variable representing applying efficiency improvement technology (e) or not.

Cic : cost of applying CO_2 capture technology (c) on unit i ($/yr)

Zic : binary variable representing applying CO_2 capture technology (c) or not.

The first term in the objective function represents the cost associated with purchasing the raw material. The second term takes into account the operating cost for different units. The cost of switching to less carbon content fuel is shown in the third term. The fourth term represents the cost associated with applying efficiency improvement technologies. The remaining term adds the cost that result from applying CO_2 capture technology. A binary variable is defined for each CO_2 mitigation option under study.

Constraints

The constraints for demand satisfaction, fuel selection and CO_2 emissions reduction are given in details as follows:

Demand satisfaction

This constraint simply says that total cement produced should be greater than or equal to the demand.

$$\sum_i \sum_f P_{if} \geq demand \tag{2}$$

Fuel selection

Each unit i has to run with only one fuel f. For that reason, a binary variable is introduced to represent the type of fuel used in a given unit.

$$\sum_{f} X_{if} = 1 \qquad \forall i \tag{3}$$

Emission constraint

The CO_2 emitted from all units must satisfy a CO_2 reduction target. Different technologies, e, to improve the efficiency are implemented in the mathematical model. It is assumed that the effect of these technologies is additive. The emission is also affected by applying CO_2 capture technology.

$$\sum_{i}\sum_{f} CO_{2if}\left(1-\sum_{e} e_{ie}Y_{ie}\right)\left(1-\sum_{c}\varepsilon_{ic}Z_{ic}\right)P_{if} \leq (1-\%CO_2)CO_2 \tag{4}$$

Where:

CO2if : CO_2 emissions from unit i using fuel f (tonne per tonne cement produced)

eie : percent gain in efficiency associated with applying technology e on unit i

Yie : binary variable for applying efficiency improvement technology e or not

εic : percent CO_2 capture

Zic : binary variable for applying CO_2 capture technology c or not

% CO2: reduction target

CO_2 : Current CO_2 emissions (tonne/yr)

The CO_2 emissions are calculated by multiplying emission factor for a given fuel with fuel consumption.

Selection of CO_2 capture process to be installed

This constraint let the model select only one capture process for each unit i

$$\sum_{c} Y_{ic} \leq 1 \qquad \forall i \tag{5}$$

Non-negativity constraints

The amount produced must be greater than zero

$$P_{if} \geq 0 \qquad \forall i \tag{6}$$

4.3 Solution Technique

The pollution control model (P) is a Mixed Integer Linear Program (MILP). It differs from Linear Programs (LP) in that its variables are restricted to have values of either 0 or 1. Mixed integer programming problems are combinatorial optimization problem that are difficult to solve. This difficulty is due to the exponential growth of solution space with a linear increase in the number of variables in the model. For instance, for a problem with twenty binary variables, the number of possible linear programs (LP) that one has to consider in an exhaustive enumeration approach is more than 1,000,000. If the number of variables is 30, then the numbers of LPs that have to be considered would be more than one billion. Hence, even for a small number of binary variables in the model, an exhaustive approach that enumerates over all possible combinations of assignments of control technologies to pollution sources, check if each combination satisfy the pollution reduction requirements, and then selects the best combination in terms of total cost would be completely intractable. Many other techniques have therefore been devised for the solution of these combinatorial optimization problems.

The most widely used method for MILP problems is the Branch-and-Bound (B&B) technique (Parker and Rardin 1988, and Rardin 1998). This technique is based on the idea of divide and conquer. Since the original "large" problem is too difficult to be solved directly, it is divided (branched) into smaller and smaller sub-problems until these sub-problems can be conquered. The branching is done by partitioning the entire set of feasible solutions into smaller and smaller subsets. The conquering (fathoming) is done partially by bounding how good the best solution in the subset can be and then discarding the subset if its bound indicates that it cannot possibly contain an optimal solution for the original problem. The B&B algorithm starts with a feasible solution to the mixed integer linear program. This solution is usually obtained from a heuristic procedure and represents a bound on the optimal solution of the problem. Then, at each iteration of the algorithm three basic steps are performed: branching, bounding, and fathoming.

The branching step fixes the value of one of the variables at zero for one subset and at one for the other subset. For each sub-problem, a relaxation is solved. The solution to the relaxation gives a bound on how good the best feasible solution of the sub-problem can be. A relaxation is obtained by deleting (relaxing) some of the constraints in the model. The most popular relaxation for binary linear programs is to relax the binary restriction on the variables of the model.

A subproblem can be conquered (fathomed), and therefore dismissed from further consideration, in three different ways. If its relaxation solution is worse than the current bound or feasible solution, if it is infeasible, or if it leads to a binary solution. In the latter case and if the solution is better than the current bound (incumbent solution), then it becomes the incumbent solution.

Each application of the above three steps represents an iteration of the B&B algorithm. The algorithm terminates when there are no more sub-problems to consider. The incumbent solution is then taken as the optimal solution. It can be shown that when the B&B is applied to an MILP with partial solution branching and candidate sub-problems (LPs) solved exactly, then the B&B stops finitely with the optimal solution (Parker and Rardin, 1988).

In order to reduce the computational expense associated with the B&B technique, a good initial solution that can serve as an upper bound to the optimal solution is often supplied. The quality of this bound has been proven to be an important factor for the success of the B&B algorithm (Elkamel et al. 1997). This is so because a large number of the constructed sub-problems by the B&B technique can be initially fathomed.

A rule based heuristic procedure that will give feasible solutions to the pollution control problem (P) can be easily formulated as a greedy heuristic. A feasible solution is any solution that satisfies the model constraints. These are respectively, the allocation constraints of new sources, existing sources, and the pollution required standards. Any heuristic procedure must be constructed in order to satisfy the above requirements.

4.4 St. Marys Plant Case Study

The developed model will be illustrated in using St. Marys Cement case study. The mathematical model developed earlier is illustrated on a case study. The problem of reducing CO_2 emissions from combustion sources within a cement plant is considered with three different mitigation options. The first option is applying efficiency improvement technology to reduce CO_2 emissions. Table 8 shows different technologies considered in this study. The second option for reducing CO_2 emissions is by switching in which the unit will be switched to operate with less carbon content fuel such as natural gas. The third option is applying CO_2 capture technologies.

Table 8: Technologies for Efficiency Improvements

Technology	**CO_2 Emission Reduction (%)**
High efficiency motors and drives	4
Adjustable Speed Drives	5.5
High efficiency classifiers	8.1
Efficient grinding technologies	10.5
Conversion from wet to dry process	50.0

An existing cement plant with the following data will be under study and the aim is to minimize the cost of cement production with reducing CO_2 emissions by a fixed target.

Cement production: 712,600 tonne/yr

Total CO_2 emissions: 553,800 tonne CO2/yr

Total annualized cost: 25 x 106 $/yr

Three CO_2 mitigation options will be considered and these are:

Applying efficiency improvement technologies to reduce CO_2 emissions shown in Table 8.

Switching to less carbon content fuel such as from coal to natural gas

Applying "end of pipe solution" CO2 capture technologies. The chemical absorption (MEA) process is the only considered option in this study with cost of 50 $/tonne CO2 captured.

The model is formulated as mixed integer nonlinear model (MINLP) and it is coded into GAMS (General Algebraic Modeling System).

The CO2 mitigation options discussed earlier are incorporated into the model to select the least cost option to reduce CO2 emissions to a specified target. Different CO2 reduction target are specified. Table 9 shows the results for different CO2 reduction targets. For 1%

reduction target, for example, the optimizer chooses to apply the technology of high efficient motors and drives. The cost of production increases by about 2 %. A second improvement technology is applied at a reduction target of 5%. No fuel switching is applied up to 10 % where efficiency improvements technologies can be applied with an increase of about 7 % in the cost. For 20 reduction target, fuel switching, from coal to natural gas, is selected to be applied with only one technology for efficiency improvement. This technology is installation of high efficient motors and drives. The cost increases by about 17 %. Carbon capture technology, MEA, is selected at a higher reduction target such as 30 %. For 50 reduction target, the optimizer still choose to apply capture technology although one of the technology for efficiency improvement technology (switch from wet to dry process) can be selected because it can achieve the same reduction target.

Table 9: Summary of Results for Different CO_2 Reduction Target

% CO_2 reduction	**Cost (million $/yr)**	**% Increase in cost**
0	25.00	0
1	25.60	2.4
5	25.72	2.9
10	26.80	7.3
20	29.35	17.4
30	33.31	33.2
50	38.85	55.4

The optimizer did not choose to apply this efficiency improvement technology because of its high cost compared to capture technology.

Figure 20 shows the increase in the production cost for each CO_2 reduction target. The line starts to be sharply increases at reduction target ranging from 20 to 50 %. This is expected since the capture cost is much higher than other mitigation options.

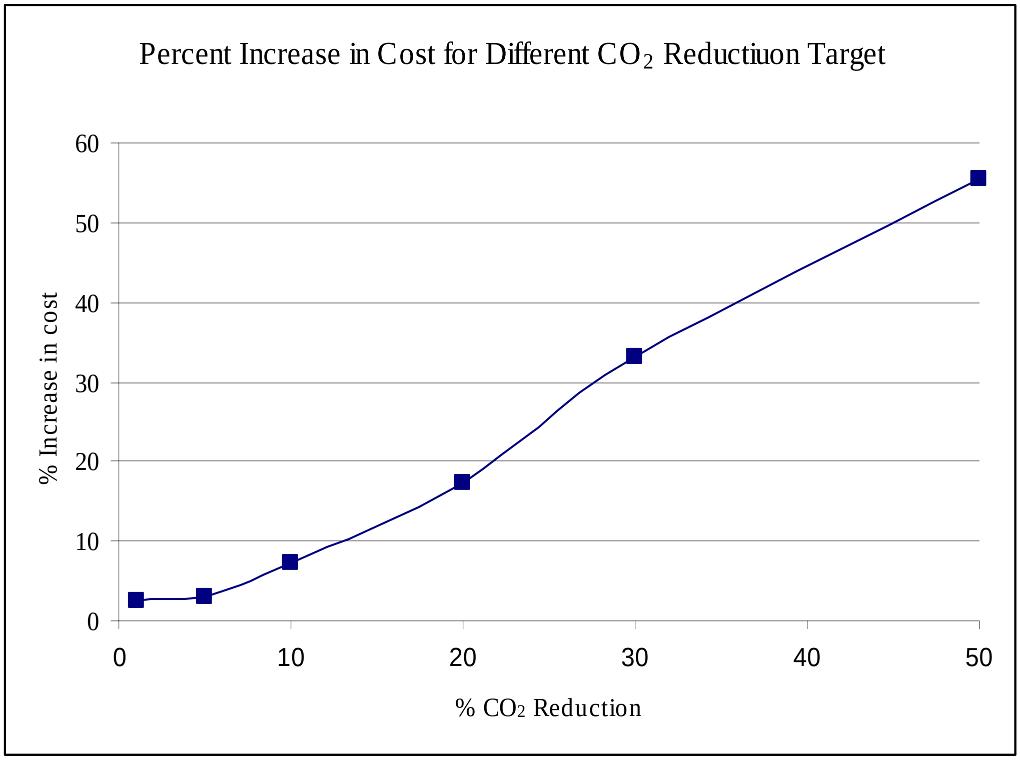


Figure 21: Percent Increase in Cost for Different CO_2 Reduction Target

Table 10 shows the cost per tonne Portland cement produced compared to the base case.

Table 10: Cost of Production per Tonne Cement

% CO_2 reduction	**Cost ($/tonne cement)**
0	35.1
1	35.9
5	36.1
10	37.6
20	41.2
30	46.7
50	54.5

4.5 Chapter Summary

Through the module results it becomes clear that future regulations related to overall CO_2 emissions will impact in the feasibility of new abatement solutions as well as current cement plants profit. Reductions over 20% will represent a challenge especially in cases where the conversion from wet process to dry process was done over 20 years ago (i.e. St. Marys Plant).

Chapter 5: Conclusion and Recommendations

At this point, it is clear that the cement industry is a key player in the sustainable development of different regions. Different alternatives discussed in this thesis can contribute to a significant progress in reducing emissions and energy waste. Improvements and solutions will need to be better coordinated and communicated with society, politicians, environmental agencies, and other institutions.

Public and political perception is a long way from full acceptance of the use of alternatives in cement production. For examples fuel substitution or the use of new raw materials is not widely accepted outside the cement industry. Alternative fuels are seen by the general public, especially in Ontario, Canada, as an incineration solution. Several states in the U.S. and different countries in Europe have been using tires as an alternative fuel source. This has not only reduced the amount of fossil fuels required by the cement plants, but it has also eliminated the landfill necessity as a final destination for old tires.

Today, a large part of the waste generated in Ontario, including tires, is shipped to the U.S. Tires and different alternative fuels find their final destination in U.S. cement kilns. The cement industry is not the final solution for waste disposal, but can clearly contribute to a solution.

In addition, the different levels of development around the globe make a universal solution unlikely. Developed countries are accountable for a higher generation of GHG emissions than developing countries and this situation will remain the same for a long time. Emerging countries have numerous social problems that, when put in competition with different environmental issues such as CO_2 generation, will require more immediate solutions. In this contest, environmental issues will have a superfluous nature.

Solutions for the cement industry must take into consideration all impacts and consequences involved in the sustainable concept. A realistic approach that considers cost, benefit, feasibility, social contribution, and environmental burden alleviation needs to be applied.

Current technological knowledge is able to achieve much better environmental performance. Therefore, the key point for emission reduction is not only a matter of technology.

Optimization model was developed in order to meet demand at a given CO_2 reduction target. Three mitigation options were considered. The model chose the best strategy or mix of strategies in order to meet a certain CO_2 reduction target with the least cost providing that the demand and other requirements were met. The model was MINLP and coded in GAMS.

Applying different efficiency improvement technologies is a good option especially at reduction target up to 10 %. Beyond that reduction target, fuel switching should be applied to achieve a reduction target such as 20 %. At reduction target higher than 20 %, carbon capture technology should be applied and efficiency improvement technologies are no more a good mitigation option. The cost of production increases dramatically when the reduction target is beyond 20 %. This is expected since carbon capture technology is the most expansive selected technology. Switching from wet to dry process was never chosen because of this technology is a natural option for cement plants to reduce cost and increase competitiveness. Actually wet system is not an option for the newer cement plants. The cost per tonne Portland cement produced increases from 35.1 $/tonne to about 55 $/tonne which is about 20 $ increase for each tonne produced.

In the specific case of the St Marys Plant, it was possible to achieve a 23.6 per cent reduction in CO_2 emissions per tonne of cement produced (Appendix 1). Unfortunately, it is not reflected in the total CO_2 emissions; St Marys actual CO_2 total emission is practically at the same level that in 1990 due to the increase in cement production.

In the specific case of the St Marys plant, it is suggested that they continue to develop partnerships with regulatory agencies to approve alternative fuels as part of the normal fuel supply operations. St Marys Cement Inc. should use successful cases from Votorantim Cement in Brazil as to gain the necessary know-how to implement environmentally friendly alternatives to fossil fuel as the primary source of energy.

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Appendix 1

Colour Codes

Subject	Numbers / Values
Basic information on plant and company	Values to be completed by Cement Company
Calculation of CO2 emissions	Calculated value
Calculation of Performance indicators, Total absolute and specific emissions	Value calculated from another part of the Worksheet
	Default value, to be corrected by Cement Company if more precise data are available

Plant Level - Comments

INFORMATION

	General Plant Information		1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000
1	Plant		
2	Company		
3	Country		
4	Continent		
5	"Kyoto" Region (Annex 1 oder Non-Annex 1)		
6	Kiln types		
7	Shares owned by Company	[%]	

	Inventory Boundaries: Coverage of Main Process Steps		1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000
7a	Raw material supply (quarrying, mining, crushing)	[yes, no or partly]	"Yes" means that consumption of fuels and electric power, and associated CO2 emissions, are reported
7b	Preparation of raw materials, fuels and additives	[yes, no or partly]	See Guide to Protocol, Annex 3, for details on the different process steps.
7c	Kiln operation (pyro-processing)	[yes, no or partly]	
7d	Cement grinding, blending	[yes, no or partly]	
7e	On-site (internal) transport	[yes, no or partly]	
7f	Off-site transport with company-owned fleets	[yes, no or partly]	
7g	On-site power generation	[yes, no or partly]	
7h	(add other process steps as appropriate)	[yes, no or partly]	

	Clinker and Cement Production		1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000
	Clinker:		
8	Clinker production	[t/yr]	Actual clinker production of active kilns
9	Clinker bought	[t/yr]	Amount of clinker purchased from other companies (internal or external Group). Does not include clinker purchased from another plant within the same Company.
10	Clinker sold	[t/yr]	Amount of clinker sold to other companies (internal or external Group). Does not include clinker dispatched to another plant within the same Company.
10a	Change in clinker stocks	[t/yr]	Amount of clinker added to stocks (positive sign) or taken from stocks (negative sign).
11	Total clinker consumed	[t/yr]	=Line8 + line9 - line10 - line10a

	Mineral components (MIC) used to produce blended cements (dry weight):		
12	Gypsum	[t/yr]	Only mineral components used for portland cement and blended cement, excl. MIC used for slag cement production
13	Limestone	[t/yr]	idem
14	Slag	[t/yr]	idem
15	Fly ash (for blending)	[t/yr]	idem
16	Puzzolana	[t/yr]	idem
17	Others	[t/yr]	idem
18	Total MIC consumed for blending	[t/yr]	=SUM (line12:line17)

	Mineral components (MIC) used as cement substitutes (direct additions to concrete):		
19a	MIC consumed for production of pure slag cement (dry weight)	[t/yr]	This is pure ground slag cement, containing no clinker
19b	Fly ash and puzzolana (direct sales, dry weight)	[t/yr]	This is pure fly ash and puzzolana, sold directly to consumers for production of concrete
19	Total pure MIC products used as cement substitutes	[t/yr]	=SUM (line19a:line19b)

	Production totals:		
20	Total Portland + Blended cements	[t/yr]	Total cement produced (all types together except pure slag cement and direct fly ash sales); = line11 + line18
21	**Total cements + substitutes**: Portland, Blended, Slag	[t/yr]	= Total cements produced, exclusive clinker sold to third parties = Portland + Blended + Slag cements incl. direct fly ash sales; = line11 + line18 + line19
21a	**Total cementitious products**	[t/yr]	= Total clinker produced plus MIC consumed for blending or production of cement substitutes; =line8 + line18 + line19

	Dust Production		1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000
22	Bypass dust discarded	[t/yr]	Only dust which leaves the kiln system (e.g., landfilling)
23	CKD sold or discarded	[t/yr]	idem
24	Calcination rate of CKD	[%]	Default = 100%

	Kiln Fuel Consumption (Aggregate)		1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000
25	Total heat consumption of kilns	[TJ/yr]	Sum of conventional fossil, fossil-based alternative and biomass fuels; =SUM (line26:28)
26	Fossil fuels	[TJ/yr]	Calculated based on consumption of individual fuels and their net calorific values; = line161
27	Alternative fuels (fossil-based, non-biomass)	[TJ/yr]	Calculated based on consumption of individual fuels and their net calorific values; = line168
28	Biomass fuels	[TJ/yr]	Calculated based on consumption of individual fuels and their net calorific values; = line175
29	Waste water	[t/yr]	Liquid waste with lower heating value < 7 GJ/t; for info only; = line121

	Non-Kiln Fuel Consumption		1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000
30	Equipment and on-site vehicles	[TJ/yr]	Fuel used for quarry equipment and vehicles for internal transport; =line321
31a	Room heating / cooling	[TJ/yr]	Fuel used for office heating; =line322
31b	Drying of raw materials	[TJ/yr]	Fuel used for drying of raw materials; =line 323
31c	On-site power generation	[TJ/yr]	Fuel used for power generation on site (autoproduction); =line324
32	Total non-kiln fuel consumption	[TJ/yr]	=SUM (line30:line31c)

	Power Consumption		1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000
33a	from on-site power generation	[MWh/yr]	Consumption of power produced on site (= from autoproduction)
33b	CO2 per power unit produced on-site	[kg CO2/MWh]	Calculated based on CO2 from on-site power generation and amount of power produced on-site; = line45c / line33a * 1000
33c	from external power generation	[MWh/yr]	Consumption of grid power
33d	CO2 per power unit produced externally	[kg CO2/MWh]	Specific CO2 emission per unit grid power, to be obtained from power supplier or national authorities
33	Total plant power consumption	[MWh/yr]	=(line33a + line33c)

	Waste Heat Exports		1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000
34	Waste heat supplied to external consumers	[GJ/yr]	Waste heat exported to third parties

CO2 EMISSIONS

Direct CO2 Emissions

	CO2 from Raw Materials		1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000
35	Calcination emission factor, corrected for CaO- and MgO imports	[kg CO2/ t cli]	Default set equal to 525 kg CO2/ t clinker. To be replaced with more precise data by Company if available (see auxiliary sheet "Calcination CO2")
36	CO2 from raw meal converted to clinker	[t CO2/yr]	Calculated from the calcination emission factor and the clinker production; =(line35 / 1000) * line8
37	CO2 from bypass dust discarded	[t CO2/yr]	Calculated from the calcination emission factor and the amount of bypass dust landfilled (assumed fully calcined); =(line35 / 1000) * line22
38	CO2 from CKD sold or discarded	[t CO2/yr]	Calculated from the calcination emission factor, the amount of CKD sold or discarded and the calcination rate of CKD; =line23 * non-linear function of lines 35 and 24; see Inventory Guide for details
39	Total CO2 from raw materials	[t CO2/yr]	=SUM (line36:line38)

	CO2 from Kiln Fuels		1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000
40	CO2 from conventional fossil fuels	[t CO2/yr]	Sum of CO2 emissions from conventional fossil fuels, = line211
41	CO2 from alternative fossil fuels (fossil wastes)	[t CO2/yr]	Sum of net CO2 emissions from fossil-based alternative fuels, = line218
43	Total CO2 from fossil-based kiln fuels	[t CO2/yr]	=SUM (line40:line41)

	CO2 from Non-Kiln Fuels		1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000
44	CO2 from equipment and on-site vehicles	[t CO2/yr]	Sum of CO2 emissions from equipment and on-site vehicles; =line331
45a	CO2 from room heating / cooling	[t CO2/yr]	Sum of CO2 emissions from room heating and cooling; =line332
45b	CO2 from drying of raw materials	[t CO2/yr]	Sum of CO2 emissions from drying of raw materials; =line333
45c	CO2 from on-site power generation	[t CO2/yr]	Sum of CO2 emissions from on-site power generation (excl. biomass CO2); =line334
46	Total CO2 from non-kiln fuels	[t CO2/yr]	=SUM (line44:line45c)

	Total Direct CO2 Emissions		1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000
48	Total direct CO2: all sources	[t CO2/yr]	= line39 + line43 + line46

	Indirect CO2 Emissions (Main Sources)		1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
49a	CO2 from external power generation	[t CO2/yr]	=line33c * line33d / 1000										
49b	CO2 from purchased clinker	[t CO2/yr]	Calculated by multiplying bought clinker by the specific direct emission per t of clinker of this plant; =line9 * line60 / 1000										
49c	Total indirect CO2 (main sources)	[t CO2/yr]	= SUM (line49a:line49b)										

	Direct CO2 from Biomass Fuels (Memo Item)		1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
50	CO2 from combustion of biomass fuels (kiln and non-kiln)	[t CO2/yr]	Direct CO2 emissions from combustion of kiln and non-kiln biomass fuels; =line225 + line334e										

PERFORMANCE INDICATORS

	Gross CO2 Emissions (= total direct CO2; all sources)		1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
59	Absolute gross CO2	[t CO2/yr]	Total direct emissions from raw material calcination, kiln fuels and non-kiln fuels; =line39 + line43 + line46										
59a	calcination component	[t CO2/yr]	Direct emissions from raw material calcination; =line39										
59b	fuel component	[t CO2/yr]	Direct emissions from kiln fuels and non-kiln fuels; =line43 + line46										
60	Specific gross CO2 per tonne of clinker produced	[kg CO2/t cli]	Total direct emissions, divided by own clinker production; =line59 / line8										
62	tonne of cementitious product	[kg CO2/t cem prod]	Total direct emissions, divided by own production of cementitious products (excluding bought clinker in cement); =line59 / line21a										
62a	calcination component	[kg CO2/t cem prod]	Direct emissions from raw material calcination, divided by own production of cementitious products; =line59a / line21a										
62b	fuel component	[kg CO2/ cem prod]	Direct emissions from kiln fuels and non-kiln fuels, divided by own production of cementitious products; =line59b / line21a										

	Credits for Indirect GHG Savings		1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
65a	Credits for indirect savings through alternative fuels (waste fuels)	[t CO2/yr]	Default = CO2 emissions from alternative fossil fuel combustion, =line41										
65b	Source of credits	[--]	Specify source of credits (e.g., based on national agreement, default assumption, etc.). Provide supporting data as appropriate.										

	Net CO2 Emissions (= gross CO2 minus credits for indirect savings)		1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
71	Absolute net CO2	[t CO2/yr]	Total direct emissions from raw material calcination, kiln fuels and non-kiln fuels, minus indirect GHG savings through alternative fossil fuels (AFR); =line59 - line65a										
71a	calcination component	[t CO2/yr]	Direct emissions from raw material calcination; =line59a										
71b	fuel component	[t CO2/yr]	Direct emissions from kiln fuels and non-kiln fuels minus indirect GHG savings through alternative fossil fuels (AFR); =line59b - line65a										
73	Specific net CO2 per tonne of clinker produced	[kg CO2/t cli]	Net emissions from raw material calcination, kiln fuels and non-kiln fuels, divided by own clinker production; =line71 / line8										
74	tonne of cementitious product	[kg CO2/t cem prod]	Net emissions from raw material calcination, kiln fuels and non-kiln fuels, divided by own production of cementitious products; =line71 / line21a										
74a	calcination component	[kg CO2/ cem prod]	Direct emissions from raw material calcination, divided by own production of cementitious products; =line71a / line21a										
74b	fuel component	[kg CO2/ cem prod]	Net emissions from kiln and non-kiln fuels, divided by own production of cementitious products; =line71b / line21a										

77	Improvement rate - net CO2 per tonne of cementitious product	[% relative to base yr]	Reduction of specific emissions relative to base year (default 1990), =(line74 yr n - line74 yr 1990) / line74 yr 1990 * 100
78	calcination component	[% relative to base yr]	Reduction of specific emissions relative to base year (default 1990), =(line74a yr n - line74a yr 1990) / line74a yr 1990 * 100
79	fuel component (fossil-based)	[% relative to base yr]	Reduction of specific emissions relative to base year (default 1990), =(line74b yr n - line74b yr 1990) / line74b yr 1990 * 100

	Specific CO2 from Indirect and Biomass Sources		1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
82	Specific indirect CO2 (power generation and clinker purchased)	[t CO2/t cem prod]	=line49c / line21a										
83	Specific CO2 from biomass fuels (Memo Item)	[t CO2/t cem prod]	=line50 / line21a										

	General Performance Indicators		1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
91	Net clinker sales / net clinker consumption	[%]	percentage of direct clinker sales versus clinker consumed to produce cement; =(line10 - line9) / line11 * 100										
92	Clinker/cement factor in cements	[%]	Clinker/cement factor in cements (exclusive clinker sold) = Total clinker consumed divided by the total of cements produced; =line11 / line21 * 100										

93	Specific heat consumption of clinker production	[MJ/t cli]	Total heat consumption of kilns divided by the clinker production; =line25 * 10^6 / line8
94	Fossil fuel rate	[%]	Fossil fuel consumption divided by the total heat consumption of kilns; =line26 / line25 * 100
95	Alternative fossil fuel rate (fossil wastes)	[%]	Alternative fossil fuel consumption divided by the total heat consumption of kilns; =line27 / line25 * 100
96	Biomass fuel rate	[%]	Biomass fuel consumption divided by the total heat consumption of kilns; =line28 / line25 * 100

97	Specific power consumption	[kWh/t cement]	Total plant power consumption divided by total cements produced; =line33 * 1000 / line21

KILN FUELS - DETAILED INFORMATION

	Kiln Fuel Consumption in tonnes per year		1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
101	**Fossil fuels**												
102	coal + anthracite + waste coal + coal/petcoke	[t/yr]	This table lists the consumption of fossil fuels in tonnes per year. Some fuel types are clustered for reasons of simplicity, but may be unclustered as appropriate										
103	petrol coke	[t/yr]											
104	(ultra) heavy fuel	[t/yr]											
105	diesel oil	[t/yr]											
106	natural gas	[t/yr]											
107	shale	[t/yr]											
108	**Alternative fossil fuels (fossil wastes)**												
109	waste oil	[t/yr]	This table lists the consumption of fossil-based AFR in tonnes per year. Some fuel types are clustered for reasons of simplicity, but may be unclustered as appropriate										
110	tyres	[t/yr]											
111	plastics	[t/yr]											
112	solvents	[t/yr]											
113	impregnated saw dust	[t/yr]											
114	other fossil based wastes	[t/yr]											
115	**Biomass fuels**												
116	dried sewage sludge	[t/yr]	This table lists the consumption of biomass or renewable AFR in tonnes per year. Some fuel types are clustered for reasons of simplicity, but may be unclustered as appropriate										
117	wood, non impregnated saw dust	[t/yr]											
118	paper, carton	[t/yr]											
119	animal meal	[t/yr]											
120	agricultural, organic, diaper waste, charcoal	[t/yr]											
121	**Waste water**	[t/yr]	This line gives the consumption of wastewater										

	Fuel Heating Values and CO2 Emission Factors			1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
130	kg CO2/GJ	fuel name												
131		**Fossil fuels**												
132	96	coal + anthracite + waste coal + coal/petcoke	[GJ/t]	Average lower heating value of fuels										
133	100	petrol coke	[GJ/t]											
134	77.4	(ultra) heavy fuel	[GJ/t]											
135	74.1	diesel oil	[GJ/t]											
136	56.1	natural gas	[GJ/t]											
137	107	shale	[GJ/t]											
138		**Alternative fossil fuels (fossil wastes)**												
139	80	waste oil	[GJ/t]	Average lower heating value of fuels										
140	85	waste tyres	[GJ/t]											
141	75	plastics	[GJ/t]											
142	75	solvents	[GJ/t]											
143	75	impregnated saw dust	[GJ/t]											
144	80	other fossil based wastes	[GJ/t]											
145		**Biomass fuels**												
146	110	sewage sludge	[GJ/t]	Average lower heating value of fuels										
147	110	wood, non impregnated saw dust	[GJ/t]											
148	110	paper, carton	[GJ/t]											
149	110	animal meal	[GJ/t]											
150	110	agricultural, organic, diaper waste, charcoal	[GJ/t]											
151		**Waste water**	[GJ/t]	As a default, the heating value of wastewater is set equal to zero.										

	Kiln Fuel Consumption in terajoules (TJ) per year		1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
161	**Fossil fuels**	[TJ/yr]	This is the sum of the individual fossil fuels. This result is registered in line 26 above										
162	coal + anthracite + waste coal + coal/petcoke	[TJ/yr]	Energy consumption calculated from kiln fuel consumption and lower heating values.										
163	petrol coke	[TJ/yr]											
164	(ultra) heavy fuel	[TJ/yr]											
165	diesel oil	[TJ/yr]											

166	natural gas	[TJ/yr]	
167	shale	[TJ/yr]	
168	**Alternative fossil fuels (fossil wastes)**	[TJ/yr]	This is the sum of the individual AFR fuels. This result is registered in line 27 above
169	waste oil	[TJ/yr]	Energy consumption calculated from kiln fuel consumption and lower heating values.
170	waste tyres	[TJ/yr]	
171	plastics	[TJ/yr]	
172	solvents	[TJ/yr]	
173	impregnated saw dust	[TJ/yr]	
174	other fossil based wastes	[TJ/yr]	
175	**Biomass fuels**	[TJ/yr]	This is the sum of the individual biomass fuels. This result is registered in line 28 above
176	sewage sludge	[TJ/yr]	Energy consumption calculated from kiln fuel consumption and lower heating values.
177	wood, non impregnated saw dust	[TJ/yr]	
178	paper, carton	[TJ/yr]	
179	animal meal	[TJ/yr]	
180	agricultural, organic, diaper waste, charcoal	[TJ/yr]	
181	**Waste water**	[TJ/yr]	Energy supplied through wastewater (default = zero)

CO2 Emissions from Kiln Fuels			1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000
211	**Fossil fuels - total emissions**	[t CO2/yr]	This is the sum of the individual fossil fuels. This result is registered in line 40 above
212	coal + anthracite + waste coal + coal/petcoke	[t CO2/yr]	This table calculates CO2 emissions by multiplying the energy consumption (in TJ/year, lines 161 ff) with the appropriate emission factors (given in lines 131ff)
213	petrol coke	[t CO2/yr]	
214	(ultra) heavy fuel	[t CO2/yr]	
215	diesel oil	[t CO2/yr]	
216	natural gas	[t CO2/yr]	
217	shale	[t CO2/yr]	
218	**Alternative fossil fuels - total emissions**	[t CO2/yr]	This is the sum of the individual AFR fuels. This result is registered in line 41 above
219	waste oil	[t CO2/yr]	This table calculates CO2 emissions by multiplying the energy consumption (in TJ/year, lines 168 ff) with the appropriate emission factors (given in lines 138ff)
220	waste tyres	[t CO2/yr]	
221	plastics	[t CO2/yr]	
222	solvents	[t CO2/yr]	
223	impregnated saw dust	[t CO2/yr]	
224	other fossil based wastes	[t CO2/yr]	
225	**Biomass fuels - total emissions**	[t CO2/yr]	This is the sum of the individual biomass fuels. This result is registered in line 50 above
226	sewage sludge	[t CO2/yr]	This table calculates CO2 emissions by multiplying the energy consumption (in TJ/year, lines 175 ff) with the appropriate emission factors (given in lines 145ff)
227	wood, non impregnated saw dust	[t CO2/yr]	
228	paper, carton	[t CO2/yr]	
229	animal meal	[t CO2/yr]	
230	agricultural, organic, diaper waste, charcoal	[t CO2/yr]	
231	**Waste water**	[t CO2/yr]	

NON-KILN FUELS - DETAILED INFORMATION

Non-Kiln Fuel Consumption in tonnes per year			1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000
301	**Equipment and On-Site Vehicles**		
301a	diesel oil	[t/yr]	This table lists the consumption of fuels used by equipment and on-site vehicles in tonnes per year. Some fuel types are clustered for reasons of simplicity, but may be unclustered as appropriate
301b	gasoline	[t/yr]	
302	**Room Heating and Cooling**		
302a	diesel oil	[t/yr]	This table lists the consumption of fuels used for room heating and cooling in tonnes per year. Some fuel types are clustered for reasons of simplicity, but may be unclustered as appropriate
302b	natural gas	[t/yr]	
303	**Drying of raw materials**		
303a	coal + anthracite + waste coal + coal/petcoke	[t/yr]	This table lists the consumption of fuels used for drying of raw materials in tonnes per year. Some fuel types are clustered for reasons of simplicity, but may be unclustered as appropriate
303b	petrol coke	[t/yr]	
303c	(ultra) heavy fuel	[t/yr]	
303d	diesel oil	[t/yr]	
303e	natural gas	[t/yr]	
303f	shale	[t/yr]	
304	**On-site power generation**		
304a	coal + anthracite + waste coal + coal/petcoke	[t/yr]	This table lists the consumption of fuels used on-site power generation in tonnes per year. Some fuel types are clustered for reasons of simplicity, but may be unclustered as appropriate
304b	(ultra) heavy fuel	[t/yr]	
304c	diesel oil	[t/yr]	
304d	natural gas	[t/yr]	
304e	biomass fuels	[t/yr]	

Fuel Heating Values and CO2 Emission Factors				1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000
310	kg CO2/GJ	fuel name		
311	**Equipment and On-Site Vehicles**			
311a	74.1	diesel oil	[GJ/t]	Average lower heating value of fuels
311b	69.2	gasoline	[GJ/t]	
312	**Room Heating and Cooling**			
312a	74.1	diesel oil	[GJ/t]	Average lower heating value of fuels
312b	56.1	natural gas	[GJ/t]	
313	**Drying of raw materials**			
313a	96	coal + anthracite + waste coal + coal/petcoke	[GJ/t]	Average lower heating value of fuels
313b	100	petrol coke	[GJ/t]	
313c	77.4	(ultra) heavy fuel	[GJ/t]	
313d	74.1	diesel oil	[GJ/t]	
313e	56.1	natural gas	[GJ/t]	
313f	107	shale	[GJ/t]	
314	**On-site power generation**			
314a	96	coal + anthracite + waste coal + coal/petcoke	[GJ/t]	Average lower heating value of fuels
314b	77.4	(ultra) heavy fuel	[GJ/t]	
314c	74.1	diesel oil	[GJ/t]	
314d	56.1	natural gas	[GJ/t]	
314e	110	biomass fuels	[GJ/t]	

Non-Kiln Fuel Consumption in terajoules (TJ) per year			1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000
321	**Equipment and On-Site Vehicles**	[TJ/yr]	This is the sum of equipment and on-site vehicles. The result is registered in line 30 above
321a	diesel oil	[TJ/yr]	Energy consumption calculated from non-kiln fuel consumption and lower heating values
321b	gasoline	[TJ/yr]	
322	**Room Heating and Cooling**	[TJ/yr]	This is the sum of room heating and cooling. The result is registered in line 31a above
322a	diesel oil	[TJ/yr]	Energy consumption calculated from non-kiln fuel consumption and lower heating values
322b	natural gas	[TJ/yr]	
323	**Drying of raw materials**	[TJ/yr]	This is the sum of drying of raw materials. The result is registered in line 31b above
323a	coal + anthracite + waste coal + coal/petcoke	[TJ/yr]	Energy consumption calculated from non-kiln fuel consumption and lower heating values
323b	petrol coke	[TJ/yr]	
323c	(ultra) heavy fuel	[TJ/yr]	
323d	diesel oil	[TJ/yr]	
323e	natural gas	[TJ/yr]	
323f	shale	[TJ/yr]	
324	**On-site power generation**	[TJ/yr]	This is the sum of on-site power generation. The result is registered in line 31c above
324a	coal + anthracite + waste coal + coal/petcoke	[TJ/yr]	Energy consumption calculated from non-kiln fuel consumption and lower heating values
324b	(ultra) heavy fuel	[TJ/yr]	
324c	diesel oil	[TJ/yr]	
324d	natural gas	[TJ/yr]	
324e	biomass fuels	[TJ/yr]	

CO2 Emissions from Non-Kiln fuels			1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000
331	**Equipment and On-Site Vehicles**	[t CO2/yr]	This is the sum of equipment and on-site vehicles. The result is registered in line 44 above
331a	diesel oil	[t CO2/yr]	This table calculates CO2 emissions by multiplying the energy consumption (in TJ/year, lines 321 ff) with the appropriate emission factors (given in lines 311 ff)
331b	gasoline	[t CO2/yr]	
332	**Room Heating and Cooling**	[t CO2/yr]	This is the sum of room heating and cooling. The result is registered in line 45a above
332a	diesel oil	[t CO2/yr]	This table calculates CO2 emissions by multiplying the energy consumption (in TJ/year, lines 322 ff) with the appropriate emission factors (given in lines 312 ff)
332b	natural gas	[t CO2/yr]	
333	**Drying of raw materials**	[t CO2/yr]	This is the sum of drying of raw materials. The result is registered in line 45b above
333a	coal + anthracite + waste coal + coal/petcoke	[t CO2/yr]	This table calculates CO2 emissions by multiplying the energy consumption (in TJ/year, lines 323 ff) with the appropriate emission factors (given in lines 313 ff)
333b	petrol coke	[t CO2/yr]	
333c	(ultra) heavy fuel	[t CO2/yr]	
333d	diesel oil	[t CO2/yr]	
333e	natural gas	[t CO2/yr]	
333f	shale	[t CO2/yr]	
334	**On-site power generation (excl. biomass fuels)**	[t CO2/yr]	This is the sum of on-site power generation (excluding CO2 from biomass fuels). The result is registered in line 45c above
334a	coal + anthracite + waste coal + coal/petcoke	[t CO2/yr]	This table calculates CO2 emissions by multiplying the energy consumption (in TJ/year, lines 324 ff) with the appropriate emission factors (given in lines 314 ff)
334b	(ultra) heavy fuel	[t CO2/yr]	
334c	diesel oil	[t CO2/yr]	
334d	natural gas	[t CO2/yr]	CO2 from biomass fuels is registered as a memo item in line 50 above
334e	biomass fuels (memo item)	[t CO2/yr]	

St. Marys Plant

INFORMATION

PERFORMANCE INDICATORS

	Gross CO2 Emissions (= total direct CO2; all sources)		1990	2000	2002	2003	2004
59	Absolute gross CO2	[t CO2/yr]	539,432	652,886	543,478	496,220	553,781
59a	calcination component	[t CO2/yr]	314,823	383,259	331,577	301,484	338,040
59b	fuel component	[t CO2/yr]	224,609	269,627	211,901	194,736	215,741
60	Specific gross CO2 per tonne of clinker produced	[kg CO2/t cli]	914	915	886	874	870
62	tonne of cementitious product	[kg CO2/t cem prod]	876	844	777	760	777
62a	calcination component	[kg CO2/t cem prod]	511	496	474	462	474
62b	fuel component	[kg CO2/ cem prod]	365	349	303	298	303

	Credits for Indirect GHG Savings		1990	2000	2002	2003	2004
65a	Credits for indirect savings through alternative fuels (waste fuels)	[t CO2/yr]	0	53,168	30,537	19,282	22,426
65b	Source of credits	[--]					

	Net CO2 Emissions (= gross CO2 minus credits for indirect savings)		1990	2000	2002	2003	2004
71	Absolute net CO2	[t CO2/yr]	539,432	599,718	512,941	476,939	531,355
71a	calcination component	[t CO2/yr]	314,823	383,259	331,577	301,484	338,040
71b	fuel component	[t CO2/yr]	224,609	216,459	181,364	175,454	193,315
73	Specific net CO2 per tonne of clinker produced	[kg CO2/t cli]	914	841	836	840	834
74	tonne of cementitious product	[kg CO2/t cem prod]	876	776	733	731	746
74a	calcination component	[kg CO2/ cem prod]	511	496	474	462	474
74b	fuel component	[kg CO2/ cem prod]	365	280	259	269	271

77	Improvement rate - net CO2 per tonne of cementitious product	[% relative to base yr]	0.0	-11.4	-16.3	-16.6	-14.9
78	calcination component	[% relative to base yr]	0.0	-3.0	-7.3	-9.6	-7.2
79	fuel component (fossil-based)	[% relative to base yr]	0.0	-23.2	-28.9	-26.3	-25.6

	Specific CO2 from Indirect and Biomass Sources		1990	2000	2002	2003	2004
82	Specific indirect CO2 (power generation and clinker purchased)	[kg CO2/t cem prod]	28	33	34	36	35
83	Specific CO2 from biomass fuels (Memo Item)	[kg CO2/t cem prod]	0	0	0	0	0

	General Performance Indicators		1990	2000	2002	2003	2004
91	Net clinker sales / net clinker consumption	[%]	44.3	22.8	13.3	8.0	15.5
92	Clinker/cement factor in cements	[%]	94.2	90.7	86.2	86.3	87.5

93	Specific heat consumption of clinker production	[MJ/t cli]	3,770	3,952	3,543	3,480	3,412
94	Fossil fuel rate	[%]	100.0	76.4	82.4	87.8	87.1
95	Alternative fossil fuel rate (fossil wastes)	[%]	0.0	23.6	17.6	12.2	12.9
96	Biomass fuel rate	[%]	0.0	0.0	0.0	0.0	0.0

97	Specific power consumption	[kWh/t cement]	195.0	142.7	147.5	144.8	155.3

Default CO2 Emission Factors for Fuels

Type	Category	IPCC default kg CO2/GJ	WGC default kg CO2/GJ	Comments
	Fossil fuels			
1	coal + anthracite + waste coal + coal/petcoke mix	96		IPCC defaults are: 94.6 for coking coal and other bituminous coal, 96.1 for sub-bituminous coal, and 98.4 for anthracite
2	petrol coke		100	
3	(ultra) heavy fuel	77.4		
4	diesel oil	74.1		
5	natural gas	56.1		
6	shale	107		
7	gasoline	69.2		
	Alternative fossil fuels			
8	waste oil		80	best estimate; water content can have relevant influence
9	tyres		85	best estimate
10	plastics		75	best estimate
11	solvents		75	best estimate
12	impregnated saw dust		75	best estimate
13	other fossil based wastes		80	best estimate
	Biomass fuels			
14	dried sewage sludge		110	= IPCC default for biomass fuels
15	wood, non impregnated saw dust		110	idem
16	paper, carton		110	idem
17	animal meal		110	idem
18	agricultural, organic, diaper waste, charcoal		110	idem

IPCC defaults from: IPCC Guidelines for National Greenhouse Gas Inventories, Vol. III
(Reference Manual), p. 1.13

Fuels have been clustered for simplicity.