The reduction of greenhouse gas emissions from the cement industry

Report Number PH3/7
May 1999

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Title: **The reduction of greenhouse gas emissions from the cement industry**
Reference number: **PH3/7**
Date issued: **May 1999**

Other remarks:

Background to the Study

The IEA Greenhouse Gas R&D programme (IEA GHG) is systematically evaluating the cost and potential for reducing emissions of greenhouse gases arising from anthropogenic activities, especially the use of fossil fuels. This is the first in a series of studies looking at opportunities for reducing greenhouse gas emissions from large energy intensive industrial sources.

Greenhouse gases are produced from a variety of industrial activities. The main sources, other than power generation, are those energy intensive industries that chemically or physically transform materials from one state to another. During these processes many greenhouse gases (carbon dioxide, methane, nitrous oxide) are released. A notable example is cement production, where considerable amounts of carbon dioxide are produced.

Carbon dioxide emitted during the cement production process represents the most important industrial source of carbon dioxide emissions outside the energy sector. Cement production accounts for 2.4% of total global industrial and energy carbon dioxide emissions. Cement production is carried out in many countries of the world. Globally, cement consumption is on the increase. The purpose of this study is to consider mitigation options in the cement industry.

This study was carried out by ECOFYS, from The Netherlands.

Industry overview

The term cement can refer to many substances that can be used as binders or adhesives. In this study it refers to inorganic hydraulic cements (principally Portland and related cements) which on hydration form relatively insoluble aggregations of considerable strength and dimensional stability. The raw materials are limestone and clay, although other suitable materials, such as pulverised fuel ash, can also be used. Figure 1 illustrates the chemistry involved as a function of temperature.

$100^{o}C$	**Evaporation of free water**
$>500^{o}C$	**Evolution of combined water (clays)**
$>900^{o}C$	**$CaCO_3 \rightarrow CaO + CO_2$**
$>900^{o}C$	**$CaO + Al_2O_3, Fe_2O_3, SiO_2$ (clinker)**
$>1200^{o}C$	**Liquid formation**
$>1280^{o}C$	**Complete reaction of CaO**

Figure 1 The basic chemistry involved in cement production

The heat for the process is supplied in rotary kilns fired using the hot flue gases of burning coal, oil or natural gas. In some cases waste materials are co-fired with the fossil fuel.

CO_2 is produced during the production of clinker, an intermediate in the cement production (Figure 1) and from the fuel used to fire the kiln. Thus CO_2 emissions are directly related to the lime content of the cement. Most cement is of the Portland variety, containing up to 67% lime. Some speciality cements have lower lime contents but these account for much smaller portions of the market.

Global emission estimates (e.g. IPCC 1995) tend to be calculated just on the basis of the clinker production. This study calculates the emissions for the whole process including the fuel for the kiln, as this gives the complete picture of anthropogenic emissions and opportunities for abatement.

Results and Discussion

The following areas are described in the report

- Production trends in the cement industry
- Cement production process
- Carbon dioxide emissions from the cement production process
- Carbon dioxide emissions from fuel use
- Global carbon dioxide emissions from cement production
- Methods of reducing carbon dioxide emissions
- Energy efficiency improvement and shifting to more energy efficient processes
- Replacing high-carbon fuels by low-carbon fuels
- Blended cements.
- Carbon dioxide removal from the process

Production trends in the cement industry

Cement production is a highly energy intensive production process. The energy consumption by the cement industry is estimated at about 2% of the global primary energy consumption, or almost 5% of total industrial energy consumption. Due to the dominant use of carbon intensive fuels, e.g. coal, in clinker-making, the cement industry is also a major emitter of CO_2. Besides energy consumption, the clinker making process also emits CO_2 due to the calcining process. Globally, the cement industry contributes 5% of global CO_2 emissions.

Global cement production grew from 594 Mt in 1970 to 1453 Mt in 1995 at an average annual growth rate of 3.6%. Data has been obtained for 10 major countries/regions.

Cement production process

Three production steps are distinguished in the production of cement:

- Preparing raw materials:
- Burning of feed materials to form cement clinker in the kiln
- Finish grinding of clinker and mixing with additives

There are two types of kiln, rotary and shaft. The former are suitable for large-scale production, the latter are small-scale. Most industrialised countries use rotary kilns while shaft kilns find widespread use in China and India.

Carbon dioxide emissions from the cement production process

Carbon dioxide emissions in cement manufacturing originate from combustion of fossil fuels and from calcining the limestone. An indirect and significantly smaller source of CO_2 is from consumption of

electricity assuming that the electricity is generated from fossil fuels. Roughly half of the emitted CO_2 originates from the fuel and half originates from the conversion of the raw material. Of the CO_2 emitted overall about 5% comes from electricity use.

Clinker contains about 64-67% CaO. The remainder consists of silicon oxides, iron oxides and aluminium oxides. The specific CO_2 emission for cement production depends on the ratio clinker/cement, which varies typically from 0.5 to 0.95. CO_2 emissions from clinker production amount to about 0.5 kg/kg clinker.

Carbon dioxide emissions from fuel use

Practically all the process fuel is used during pyroprocessing in the production of the clinker. The pyroprocess removes water from the raw mixture, calcines the limestone at temperatures between 900 and 1000 °C and finally clinkers the raw materials at about 1500 °C. The amount of carbon dioxide emitted during this process is influenced by the type of fuel used (coal, fuel oil, natural gas, petroleum coke, alternative fuels). The total CO_2 emission during the cement production process depends mainly on:

- Type of production process (efficiency of the process and sub-processes)
- Fuel used (coal, fuel oil, natural gas, petroleum coke, alternative fuels)
- Clinker/cement ratio (percentage of additives)

Global carbon dioxide emissions from cement production

Estimated carbon dioxide emissions from cement production in 1994 were 1126 Mt CO_2[1], 587 Mt CO_2 from process emissions and 539 Mt CO_2 from energy use. The world average emissions from cement production is 0.81 kg CO_2/kg cement. Table 1 gives an overview of the emissions from cement production in 10 regions.

	Cement Production	Primary Intensity	Primary Energy	Process Carbon Emissions	Carbon Emissions. Energy Use	Total Carbon Emissions	Share of World Total
Country/Region	Mt	MJ/kg	PJ	Mt CO_2	Mt CO_2	Mt CO_2	%
China	423	5.0	2117	175	197	372	33.0
Europe	182	4.1	749	73	56	130	11.5
OECD Pacific	151	3.5	533	65	41	105	9.3
Other Asia	124	4.9	613	56	49	105	9.3
Middle East	111	5.1	563	51	44	95	8.4
North America	88	5.4	480	39	40	78	7.0
EE/FSU[2]	101	5.5	558	42	38	80	7.1
Latin America	97	4.7	462	41	30	71	6.3
India	62	5.0	309	28	30	58	5.1
Africa	41	4.9	201	18	15	33	2.9
World Total	1381	4.8	6585	587	539	1126	100.0

Table 1. 1994 Global Carbon Emissions from Cement Production

Methods of reducing carbon dioxide emissions

Emissions of carbon dioxide can be reduced by:

- improvement of the energy efficiency of the process

[1] 1 Mt CO_2 = 0.27 Million tonne Carbon (MtC) = 0.27 TgC
[2] Eastern Europe/Former Soviet Union

- shifting to a more energy efficient process (e.g. from wet to dry process)
- replacing high carbon fossil fuels by low carbon fossil fuels
- replacing fossil fuels by alternative fuels, e.g. waste-derived fuels
- applying lower clinker/cement ratio (increasing the ratio additives/cement): blended cements.
- application of alternative cements (mineral polymers)
- removal of CO_2 from the flue gases

Energy efficiency improvement and shifting to more energy efficient processes

Improvement of energy efficiency reduces the emissions of carbon dioxide from fuel and electricity uses, and may reduce the costs of producing cement. Improvement may be attained by applying more energy efficient process equipment and by replacing old installations by new ones or shifting to completely new types of cement production processes. Possibilities include:

- conversion from direct to indirect firing;
- improved recovery from coolers, and
- installation of roller presses, vertical mills and high efficiency separators.

By far the largest proportion of energy consumed in cement manufacture consists of fuel that is used to heat the kiln. Therefore the greatest gain in reducing energy input may come from improved fuel efficiency.

Replacing high-carbon fuels by low-carbon fuels

Fuel use accounts for more than 90% of the final energy used in the cement production. The rest (up to 10%) of the primary energy consumption is electricity. An important option to reduce carbon dioxide emissions is to reduce the carbon content of the fuel: e.g. shifting from coal to natural gas.

Some types of alternative fuels are:

- Gaseous alternative fuels (Coke oven gases, refinery gases, pyrolysis gas, landfill gas);
- Liquid alternative fuels (Halogen-free spent solvents, mineral oils, distillation residues, hydraulic oils, insulating oils);
- Solid alternative fuels (Waste wood, dried sewage sludge, plastic, agricultural residues, tyres, petroleum coke, tar).

The net reduction of CO_2 emissions depends on the nature and characteristics of the wastes, as well as the alternative waste treatment process which would be used.

Blended cements

Another way to reduce the energy used for making clinker is to replace some of it with other materials. In blended cement, a portion of the clinker is replaced with industrial by-products such as coal fly ash (a residue from coal burning) or blast furnace slag (a residue from ironmaking), or other pozzolanic materials (e.g. volcanic material). These products are blended with the ground clinker to produce a homogenous product; blended cement. The global potential for carbon dioxide emission reduction through producing blended cement is estimated to be at least 5% of total carbon dioxide emissions from cement making (56 Mt CO_2), but may be as high as 20%. The potential savings will vary by country, and by region. The benefits of avoided emissions may have to be shared with the industry producing the clinker.

Carbon dioxide removal

The CO_2 can be recovered from the flue gases from the calcination process as well as from the combustion process. Typical CO_2 concentrations in the flue gases range from 14 to 33%. There are a number of possible CO_2 separation techniques and the report examines each of the main ones.

Because of the high share of CO_2 in flue gases originating from the calcination stage, combustion in a CO_2/O_2 atmosphere may be a promising technique to recover the CO_2. A chemical absorption process for CO_2 separation seems less appropriate because of the high heat requirement of the process, which is not easily available from the cement production process.

In the CO_2/O_2 technique, oxygen instead of air is used for the combustion, i.e. the nitrogen is removed in an air separation plant before the fuel is oxidised. A potential problem in this approach is the high temperature of stoichiometric combustion. This problem can be solved, and even turned into an advantage, by recycling produced CO_2. In this way adding more or less recycled CO_2 can control the combustion temperature. The CO_2 in such systems moderates the combustion temperature. Experience with the CO_2/O_2 combustion technique has been gained in projects related to power generation in Canada, Japan and the United States. It is not considered that firing the kiln on CO_2/O_2 will increase plant capacity.

In comparison with the production plant without CO_2-removal, a number of aspects should be further explored: control of leakage of air into the kiln; cooling tract of the cement after the kiln; energy balance of the system; consequence of the higher CO_2-partial pressure on the calcination process; and control needed to reduce emission of CO_2 during start-up and shut-down of the cement plant.

In the scope of this study a preliminary calculation on the energy requirement has been made (including air separation), assuming 90% capture efficiency, a dry process (3.35 MJ/kg clinker), and a clinker/cement ratio of 0.95. The total required power consumption will be about 0.9-1.0 MJ/kg cement in this case. The total CO_2 production amounts then to 1.1 kg/kg cement (fuel: coal) or to 0.9 kg/kg cement (fuel: natural gas), and the overall capture efficiency amounts to 65%. The net CO_2 emission amounts to 0.38 kg per kg cement (fuel: coal) and 0.34 kg per kg cement (fuel: natural gas).

Results for carbon dioxide emission reduction

Table 2 gives an overview of the identified options to reduce carbon dioxide emissions. The table gives an indication of the reduction potential in a cement plant and globally the cost (or savings) of each option.

	CO_2 emission reduction potential		Costs (\$/t CO_2 avoided)
	plant-based	Global	
Efficiency improvement measures	0-20%	-	Range from benefits to high costs
Dry process	20-40%	10-15%	Retrofitting: ranges from benefits of 50-150 to low costs
High carbon to low carbon fuels	10-20%	15%	25-50
Application of waste	20-40%	30%	Range from benefits to small costs
Increasing use of additives	0-25%	30-35%	Benefits
Alternative cements	na	80%	
CO_2-removal	60-65%	-	50-250

Table 2. Overview of options for reducing carbon dioxide emissions

Expert Group Comments

The draft version of this report was sent to the eight experts identified by the Programme's members and from the cement industry. The general opinion was good and many of the comments were editorial although there were a number of specific requests. Most of the requests recommended by the expert group have been incorporated into the report, including most significantly to contact further cement manufacturers and to firm up and include cost data.

Major Conclusions

Carbon dioxide emissions from cement production contribute significantly to total global carbon dioxide emissions. Emissions may grow substantially in the short and long-term. In a base line scenario of 'frozen efficiency', carbon dioxide emissions may almost double in the next 25 years from 345 MtC in 1995 to 652 MtC in 2020 (i.e. 90% increase). A scenario of 'moderate' effort may reduce *the increase* of emissions to about 60%.

The share of process-related emissions (i.e. not including the fuel) will become relatively higher, because fewer measures are available to decrease process-related emissions. In a 'high' effort scenario, assuming considerable improvements, emissions may grow by only 35%. In this scenario emissions related to fuel use will decrease by 3%. The relative share of the fuel-related emissions will decrease from the present 45% to 32-39%.

A range of measures has been identified which could achieve useful reductions in emissions, some with savings in overall expenditure. The only technique identified which could effect deep reductions in emissions is CO_2 removal. Estimates of the cost of this range from \$50-250/t CO_2 avoided.

Recommendations

A follow up study could look in more detail at alternative ways of building or of making cement, to avoid the use of calcium carbonate.

An additional study could also concentrate on a number of example plants and on a site-specific basis look at all the emissions and costs from a complete life cycle basis.

More detailed study of CO_2 removal on plant basis would provide greater certainty in the cost and performance figures.

The emergence of a trading system for CO_2 emissions credits may improve the economics of the cement industry. The impact of such a system on the cement industry's economics and investment is recommended, perhaps examining CO_2 storage credits as case studies.

Greenhouse Gases from Cement Production

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January 1999

By order of the IEA Greenhouse Gas R&D Programme

M 716

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SUMMARY

Cement is considered one of the most important building materials around the world. It is mainly used for the production of concrete. Concrete is a mixture of inert mineral aggregates, e.g. sand, gravel, crushed stones, and cement. Cement consumption and production is closely related to construction activity, and therefore to the general economic activity. Cement is one of the most produced materials around the world. Due to the importance of cement as a construction material, and the geographic abundance of the main raw materials, i.e. limestone, cement is produced in virtually all countries. The widespread production is also due to the relative low price and high density of cement, that limits ground transportation because of the relative high costs. Generally, the international trade is limited to less than 10%, when compared to the global production.

Cement production is a highly energy intensive production process. The energy consumption by the cement industry is estimated at about 2% of the global primary energy consumption, or almost 5% of the total global industrial energy consumption. Due to the dominant use of carbon intensive fuels, e.g. coal, in clinker making, the cement industry is also a major emitter of CO_2 emissions. Besides energy consumption, the clinker making process also emits CO_2 due to the calcining process. The cement industry contributes 5% of total global carbon dioxide emissions. Therefore researchers associated with Ecofys Energy and Environment (Netherlands) and Lawrence Berkeley National Laboratory (USA) made for the IEA Greenhouse Gas R&D Programme an assessment to the role of the cement industry in CO_2 production and to carbon dioxide emission reduction options.

Historical production trends in the cement industry

Global cement production grew from 594 Mt[1] in 1970 to 1453 Mt in 1995 at an average annual growth rate of 3.6%. Table 1.1 provides historical cement production trends and average annual growth rates for 10 world regions and countries. The regions with the largest production levels in 1995 were China (including Hong Kong), Europe, OECD-Pacific, Rest of Asia, and the Middle East. The largest average annual growth between 1970 and 1995 was seen in China (12.2% per year), Rest of Asia (7.8% per year), Middle East (7.4% per year), and India (6.6% per year) regions. Growth in Africa (4.5% per year), Latin America (4.1% per year), and OECD-Pacific (3.3% per year) was also relatively high. In contrast, there was very little growth in production in the North America region, and production levels dropped at an average rate of -0.1% per year in Europe during this period. The Eastern Europe/former Soviet Union region showed the largest declines in cement production, averaging –1.3% per year between 1970 and 1995.

Cement production process

Four production steps are distinguished in the description of the production of cement:

- Quarrying and mining: mining of the raw materials.
- Preparing raw materials: Mixing/homogenising, grinding and preheating (drying) produces the *raw meal*.

[1] 1 Mt = 1 million tonne = 10^9 kg = 1 Tg

- Burning of raw meal to form cement clinker in the kiln: The components of the raw meal react at high temperatures (900-1500 °C) in the rotary kiln, to give clinker.
- Finish grinding of clinker and mixing with additives: After cooling the clinker is ground together with additives.
-

Table 1.1. Cement Production Trends and Average Annual Growth Rates for Major World Regions, 1970-1995 Source: Cembureau, 1998.

	Cement Production						Average Annual Growth	
	1970	1975	1980	1985	1990	1995	1970-1995	1990-1995
	Mt	Mt	Mt	Mt	Mt	Mt	%	%
China (incl. Hong Kong)	27	47	81	148	211	477	12.2%	17.7%
Europe	185	194	223	178	196	181	-0.1%	-1.7%
OECD-Pacific	69	83	113	100	126	154	3.3%	4.1%
Rest of Asia	20	31	49	57	89	130	7.8%	8.0%
Middle East	19	29	44	75	93	116	7.4%	4.6%
Latin America	36	52	76	71	82	97	4.1%	3.4%
Eastern Europe/ Former Soviet Union	134	177	190	190	190	96	-1.3%	-12.7%
North America	76	73	79	81	81	88	0.5%	1.5%
India	14	16	18	31	49	70	6.6%	7.3%
Africa	15	20	28	35	38	44	4.5%	2.7%
World	594	722	901	965	1156	1453	3.6%	4.7%

The theoretical minimal energy requirement for clinker making, the main substance of cement, is calculated to be about 1.75 ± 0.1 MJ per kg. The actual heat requirement is higher, and depends on the type of process applied. There are two types of kiln, rotary and shaft. The former are suitable for large-scale production, the latter are small-scale. Most industrialised countries use rotary kilns while shaft kilns find widespread use in China and India. Rotary kilns can be divided into three types, wet, semi-wet (or semi-dry) and dry processes. Dry process kilns can be further subdivided into long dry kilns, kilns with suspension preheaters and kilns with preheaters and precalciners. Table 1.2 gives a summary of energy use of the various cement production processes.

Table 1.2. Summary table of the typical energy use of the main cement production processes (MJ per kg clinker).

	Rotary Kilns				Shaft Kiln
	Wet	Lepol	Long dry	Short dry kiln	
Fuel use (MJ/kg)	5.9	3.6	4.2	2.9 - 3.4	3.7 - 6.6
Power use kiln (kWh/kg)	0.025	0.030	0.025	0.022	
Primary energy (MJ/kg)	6.2	3.9	4.5	3.5 - 3.7	

Carbon dioxide emissions from the cement production process

Carbon dioxide emissions in cement manufacturing originate from combustion of fossil fuels and from calcining the limestone in the raw mix. An indirect and significantly smaller source of CO_2 is from consumption of electricity assuming that the electricity is generated from fossil fuels. Roughly half of the emitted CO_2

originates from the fuel and half originates from the conversion of the raw material.

Carbon Dioxide Emission from Calcination (Process Emissions)

Process CO_2 is formed by calcining which can be expressed by the following equation:

$$\underset{1\ kg}{CaCO_3} \rightarrow \underset{0.56\ kg}{CaO} + \underset{0.44\ kg}{CO_2}$$

The share of CaO in clinker amounts to 64-67%. The remaining part consists of silicium oxides, iron oxides and aluminium oxides. CO_2 emissions from clinker production amounts therefore at about 0.5 kg/kg clinker. The specific process CO_2 emission for cement production depends on the ratio clinker/cement. This ratio varies typically from 0.5 to 0.95.

Carbon Dioxide Emissions from Fuel Use

Practically all fuel is used during pyroprocessing in the production of the clinker. The pyroprocess removes water from the raw meal, calcines the limestone at temperatures between 900 and 1000 °C and finally clinker the raw materials at about 1500 °C. The amount of carbon dioxide emitted during this process is influenced by the type of fuel used (coal, fuel oil, natural gas, petroleum coke, alternative fuels).

The total CO_2 emission during the cement production process depends mainly on:

- Type of production process (efficiency of the process and sub-processes)
- Fuel used (coal, fuel oil, natural gas, petroleum coke, alternative fuels)
- Clinker/cement ratio (percentage of additives)

Table 1.3 shows the carbon dioxide emission from the cement production (dry and wet-process) in relation to the clinker/cement ratio and fuel used. The cement/clinker ratio may vary by adding more or less additives to the cement. Not accounted for are the carbon dioxide emissions attributable to mobile equipment used for winning of raw material, used for transport of raw material and cement, and used on the plant site.

Table 1.3. CO_2 emissions in kg per kg cement produced for dry and wet cement production process for various fuels and various clinker/cement ratios. Assumptions: Electricity use: 0.38 MJe/kg of clinker; Average emission factor of CO_2 of electricity production: 0.22 kg/MJe. Fuel use (dry process): 3.35 MJ/kg of clinker; (wet process): 5.4 MJ/kg of clinker.

	Process emissions	Process and fuel-related emissions			
Clinker/cement ratio	**Clinker**	**Coal**	**Fuel Oil**	**Natural gas**	**Waste[a]**
Dry process					
55%	*0.28*	0.55	0.50	0.47	0.36
75%	*0.38*	0.72	0.66	0.61	0.47
(Portland) 95%	*0.49*	0.89	0.81	0.75	0.57
Wet Process					
55%	*0.28*	0.67	0.59	0.53	0.36
75%	*0.38*	0.88	0.77	0.69	0.47
(Portland) 95%	*0.49*	1.09	0.95	0.90	0.57

[a] assumed a 100% fuel coverage by waste and a waste CO_2 emission factor of zero. Depending on the alternative waste processing technology, i.e. with or without energy recovery, this factor may be higher, leading to higher nett CO_2 emissions.

Global carbon dioxide emission from cement production process

The world average primary specific energy consumption is estimated at 4.8 MJ/kg cement, with the most energy intensive regions being Eastern Europe and the former Soviet Union (5.5 MJ/kg), North America (5.4 MJ/kg) and the Middle East (5.1 MJ/kg). Estimated carbon dioxide emissions from cement production in 1994 were 1126 Mt CO_2,[1] 587 Mt CO_2 from process emissions and 539 Mt CO_2 from energy use. These emissions account for 5% of 1994 world carbon emissions based on a total of 22.7 10^3 Mt CO_2 (6.2 GtC) reported by the Carbon Dioxide Information and Analysis Center. The average world carbon intensity of carbon emissions in cement production is 0.81 kg CO_2/kg cement. While China is the largest emitter, the most carbon intensive cement region in terms of carbon emissions per kg of cement produced is India (0.93 kg CO_2/kg), followed by North America (0.89 kg CO_2/kg), and China (0.88 kg CO_2/kg).
This estimate is based on current, publicly available data for the cement sector, using clinker and cement production figures, energy intensities, and fuel mix for cement and electricity production. Table 1.4 gives an overview of the global carbon emissions from cement production.

Table 1.4. 1994 Global Carbon Emissions from Cement Production

Country/Region	Cement Production	Clinker/ Cement Ratio	Primary Intensity	Primary Energy	Process Carbon Emissions	Carbon Emissions. Energy Use	Total Carbon Emissions	Share of World Total
	Mt	%	MJ/kg	PJ	Mt CO_2	Mt CO_2	Mt CO_2	%
China	423	83%	5.0	2117	175	197	372	33.0%
Europe	182		4.1	749	73	56	130	11.5%
OECD Pacific	151		3.5	533	65	41	105	9.3%
Other ASIA	124		4.9	613	56	49	105	9.3%
Middle East	111		5.1	563	51	44	95	8.4%
North America	88		5.4	480	39	40	78	7.0%
EE/FSU	101		5.5	558	42	38	80	7.1%
Latin America	97		4.7	462	41	30	71	6.3%
India	62	89%	5.0	309	28	30	58	5.1%
Africa	41		4.9	201	18	15	33	2.9%
World Total	1381		4.8	6585	587	539	1126	100.0%

Reduction of carbon dioxide emissions

Emissions of carbon dioxide can be reduced by:

- improvement of the energy efficiency of the process
- shifting to a more energy efficient process (e.g. from wet to dry process)
- replacing high carbon fossil fuels by low carbon fossil fuels
- replacing fossil fuels by alternative fuels, e.g. waste-derived fuels
- applying lower clinker/cement ratio (increasing the ratio additives/cement): blended cements.
- application of alternative cements (mineral polymers)
- removal of CO_2 from the flue gases

Energy Efficiency Improvement and Shifting to More Energy Efficient Processes

Improvement of energy efficiency reduces the emissions of carbon dioxide from fuel and electricity uses, and may reduce the costs of producing cement. Improvement may be attained by applying more energy efficient process equipment and by

[1] 1 Mt CO_2 = 0.27 Million tonne Carbon (MtC) = 0.27 TgC

replacing old installations by new ones or shifting to complete new types of cement production processes.
Important energy efficiency improvement possibilities are: (i) conversion from direct to indirect firing; (ii) improved recovery from coolers, and (iii) installation of roller presses, vertical mills and high efficiency separators.

Table 1.5. Energy efficiency improvement options for cement production processes

Technique	Description	Emission reduction/ energy improvement	Economics
Process Control and Management Systems	Automated computer control may help to optimise the combustion process and conditions	Typically 2.5-5%	Economics of advanced processes very good (pay back time as short as 3 months)
Raw Meal Homogenising Systems	Use of gravity-type homogenising silos	Reduction power use (1.4-4 kWh/t clinker)	No information available for this study
Conversion from Wet to Semi-Wet Process	Moisture content of raw meal reduced by slurry press filter.	0.8-1.6 GJ/t clinker (3-5 kWh increase of power consumption)	Reduced fuel costs partially offset the costs.
Conversion from Wet to Dry Process	Complex operation, leaving only the structural parts intact	Estimated at 2.2 GJ/t (increase of power by about 10 kWh/t)	High costs (133 US$/t annual capacity), but vary across the world. May be economically feasible
Conversion from dry to multi-stage preheater kiln	Four or five stage preheating reduces heat losses, and sometimes reduces pressure drop	Depending on original process. In one example reduction from 3.9 to 3.4 GJ/t	Estimated at 30-40 US$/t annual capacity
Conversion from dry to precalciner kiln	Increase of capacity, and lowering specific fuel consumption	Depending on original process. Estimated at 12% (0.44 GJ/t)	Estimated at 28 US$/t annual capacity
Conversion from Cooler to Grate Cooler	Large capacity and efficient heat recovery.	Reduction of 0.1-0.3 GJ/t (increase in power by 3 kWh/t)	Probably only attractive when installing a precalciner simultaneously
Improved Preheating (LEPOL Kiln)	Raw meal preheated in a two-stage grate preheater.	Fuel saving of 6.3% (to 3.3 GJ/t). 1% less power use	Payback time reported to be satisfactory
Optimisation of Heat Recovery in Clinker Cooler	Heat recovery improved by reduction of excess air volume, control of clinker bed depth and new grates.	Estimated at 0.5 GJ/t in the US, and 0.2 GJ/t in India	No specific cost information available for this study
High efficiency Motors and Drives	Variable speed drives, improved control strategies and high-efficiency motors	Estimated power savings ranging from 3 to 8%.	High-efficiency motors cost about the same or only little bit more than regular motors
Adjustable Speed Drives	Reducing throttling and coupling losses by replacing fixed speed AC motors	Estimated at 10 kWh/t cement	Depends strongly on size of system. Estimated at about 1 US$/t cement
Efficient Grinding Technologies	High-pressure mills (like the Horomill) has improved grinding characteristics	Estimated at 16-19 kWh/t (40-50%)	Estimates ranging from 2.5 to 8 US$/t annual capacity. Operation costs may be reduced by 30-40%
High-efficiency Classifiers	sharper separation, thus reducing overgrinding	Estimated at 1.7-2.3 kWh/t cement (8%)	Costs are estimated at 2.5-3 US$/t cement
Shaft Kilns: Efficient Kiln Technology (China)	Improved input control, kiln size and shape, insulation and computer control.	Estimated at 1.2 GJ/t for the 1990 mix (10-30%)	Investment estimated at 230 Yuan/t annual capacity. Pay back time of less than 2 years.
Fluidised bed Kiln	Rotary kiln replaced by stationary kiln leading to lower capital costs, wider variety of fuel use and lower energy use	Fuel use of 2.9 to 3.35 GJ/t clinker (also lower NO_x emissions)	Lower investment and maintenance costs expected
Advanced Comminution Technologies	Non-mechanical 'milling' technologies as ultrasound. Not commercially available in coming decades	Expected (theoretical) savings are large	No information available due to preliminary stage of development
Mineral Polymers	Mineral polymers are made from alumino-silicates leaving calcium oxide as the binding agent.	Preliminary estimates suggests 5 to 10 times lower energy use and emissions	No specific cost information was available for this study.

By far the largest proportion of energy consumed in cement manufacture consists of fuel that is used to heat the kiln. Therefore the greatest gain in reducing energy input may come from improved fuel efficiency.

Another approach to improve energy efficiency is to shift to another cement production technology. In general it can be said that the dry process is much more energy efficient than the wet process. The processes are exchangeable to a large extent, but the applicability also depends on the raw material available. Table 1.5 gives the main options to improve the energy efficiency of cement production facilities.

Replacing High-Carbon Fuels by Low-Carbon Fuels

Fuel use accounts for more than 90% of the final energy used in the cement production. The rest (up to10%) of the primary energy consumption is electricity. An important option to reduce carbon dioxide emissions is to reduce the carbon content of the fuel: e.g. shifting from coal to natural gas. An important opportunity to reduce the (long-cycle) carbon emission is the application of waste-derived alternative fuels. This could at the same time diminish the disposal of waste material and reduces the use of fossil fuels. Disadvantage may be the adverse effects on the cement quality and increased emission of harmful gases. It should be noted that emissions generally depend more on kiln operation conditions than on type of fuel. Some types of alternative fuels: Gaseous alternative fuels (Coke oven gases, refinery gases, pyrolisis gas, landfill gas); Liquid alternative fuels (Halogen-free spent solvents, mineral oils, distillation residues, hydraulic oils, insulating oils); and Solid alternative fuels (Waste wood, dried sewage sludge, plastic, agricultural residues, tyres, petroleum coke, tar). The net reduction of CO_2 emissions depends on the nature and characteristics of the wastes, as well as the waste treatment process used, which would be used alternatively.
The European cement industry used in 1990 between 0.75 and 1 Mt per year of alternative fuels, equivalent to 25-35 PJ. In 1993, 9% of the thermal energy consumption in the European cement industry originated from alternative fuels. A number of issues should be considered while using waste-derived fuels: (i) energy efficiency of waste combustion in cement kilns; (ii) constant cement product and fuel quality; (iii) emissions to atmosphere; (iv) trace elements and heavy metal; (v) alternative fate of waste; and (vi) production of secondary waste.

Waste processing in the cement industries is feasible and current practice. Waste as alternative fuel is increasingly used in cement plants. Waste may reduce CO_2 emissions by 0.1 to 0.5 kg/kg cement produced compared to current used production techniques using fossil fuels. The use of waste generates no additional emissions, although care should be taken for high volatile elements as mercury and thallium.

Blended Cements.

The production of clinker is the most energy-intensive step in the cement manufacturing process and causes large process emissions of CO_2. In blended cement, a portion of the clinker is replaced with industrial by-products such as coal fly ash (a residue from coal burning) or blast furnace slag (a residue from iron making), or other pozzolanic materials (e.g. volcanic material). These products are blended with the ground clinker to produce a homogenous product; blended cement.

The future potential for application of blended cements depends on the current application level, on the availability of blending materials, and on standards and legislative requirements. Worrell *et al*. [1995] tried to estimate the potential for carbon emission reduction on a national basis for 24 countries in the OECD, Eastern

Europe and Latin-America. They estimated the minimum availability of blending materials on the basis of pig iron production and coal combustion. The potential emission reduction varied between 0% and 29%. The average emission reduction for all countries (producing 35% of world cement in 1990) was estimated at 22%. It was negligible for countries with already a large share of blended cement production (e.g. The Netherlands) or with a low availability of blending materials; i.e. countries without iron production or coal fired power stations (e.g. Costa Rica, Guatemala). It is high for countries without much production of blended cements and a well-developed industry or fossil based power industry (e.g. United Kingdom, United States). The clinker/cement ratio for China is estimated at 85%. Considering the large iron production and coal use in power production in China, a large potential for blended cement may also be expected in the World's largest cement maker.

The costs of blending materials depend strongly on the transportation costs, and may vary between 15 and 30 US$/t for fly ash and approximately 24 US$/t for blast furnace slag. Shipping costs may increase the price significantly, depending on distance and shipping mode. The prices are still considerably lower than the production costs of cement, estimated at approximately 36 US$/t (1990) in the United States.

Summarising, the global potential for carbon dioxide emission reduction through producing blended cement is estimated to be at least 5% of total carbon dioxide emissions from cement making (56 Mt CO_2), but may be as high as 20%. The potential savings will vary by country, and by region.

Carbon Dioxide Removal

Reduction of carbon dioxide emissions can be obtained by applying carbon dioxide removal. In this technique, CO_2 is separated during or after the production process and subsequently stored or disposed of outside the atmosphere. The CO_2 removal process can be split into three separate steps: recovery of the CO_2 (often including drying and compressing), transport of the CO_2 to a location where it is handled further, and utilisation, storage or disposal of CO_2. Storage can, for instance, take place in aquifers (water-containing layers) or in depleted natural gas fields. Studies indicates that there is a considerable storage potential (hundreds of GtC) accessible at moderate costs. In some cases the recovered CO_2 can be used for other purposes. The CO_2 can be recovered from the flue gases, originating from the calcination process as well as from the combustion processes. Typical CO_2-concentrations in the flue gases range from 14 to 33%.

Because of the high share of CO_2 in flue gases originating from the calcination process (and not from a combustion process), combustion in a CO_2/O_2 atmosphere may, a priori, be a promising technique to recover the CO_2. A chemical absorption process seems to be less appropriate because of the high heat requirement of the process, which seems not available from the cement production process.
In the CO_2/O_2 technique oxygen instead of air is used for the combustion, i.e. the nitrogen is removed in an air separation plant before the fuel is oxidised. A problem in this approach is the high stoichiometric combustion temperatures. This problem can be solved, and even turned into an advantage, by recycling produced CO_2. In this way adding more or less recycled CO2 can control the combustion temperature. The CO_2 in these systems acts as the required temperature moderator.

An additional benefit is that all impurities are stored underground, and that the need for DeSOx or DeNOx facilities is not present. Experiences with this technique have been gained in projects related to power generation in Japan and the United States.
In principle this process could be applied to cement production process. A mixture of oxygen and carbon dioxide is fed to the burner in the kiln. The oxygen should be produced in a nearby oxygen plant, the carbon dioxide is recycled from the exhaust of the kiln. In comparison with the production plant without CO_2-removal a number of aspects should be further explored: control of leakage of air into the kiln; cooling route of the cement after the kiln; energy balance of the system; consequence of the higher CO_2-partial pressure on the calcination process; and control to reduce emission of CO_2 during start/stops of the cement plant.
In the scope of this study a preliminary calculation on the energy requirement has been made: assuming 90% capture efficiency, dry process (3.35 MJ/kg clinker), clinker/cement ratio of 0.95, the total required power consumption will be about 0.9-1.0 MJe/kg cement. The total CO_2 production amounts then to 1.1 kg/kg cement (fuel: coal) or to 0.9 kg/kg cement (fuel: natural gas), and the overall capture efficiency amounts to 65%. The net CO_2 emission amounts to 0.38 kg per kg cement (fuel: coal) and 0.34 kg per kg cement (fuel: natural gas).

Table 1.6 gives an overview of the identified options to reduce carbon dioxide emissions. The table gives an indication of the reduction potential in a cement plant and a cost range the option can most probably can be implemented.

Development of carbon dioxide emissions in the short and mid-long term

Carbon dioxide emissions from cement production contribute significantly to total global carbon dioxide emission. Emissions may grow substantially in the short and long-term period. In a 'frozen efficiency' base line scenario, carbon dioxide emission may almost double in the next 25 years from 345 MtC in 1995 to 652 MtC in 2020. A 'moderate' effort (scenario-1) reducing the projected base line emissions may reduce *the increase* of the emissions to about 44%. The share of process-related emissions will become relatively higher, because fewer measures are available to decrease process-related emissions. In a 'high' effort scenario (scenario-2), assuming considerable improvements, emissions may grow still by 26%. In this scenario emission related to fuel use will decrease by 21%, while process-related emissions grow by 71%. The relative share of the fuel-related emissions will decrease from the present 45% to 34% (scenario-1) or to 28% (scenario-2). The share of process-related emissions increase from the present 46% to 57% (scenario-1) or to 63% (scenario-2).

Table 1.6. Overview of carbon dioxide reduction options

	CO_2 emission reduction potential		Costs (US$/t CO_2 avoided)	Remarks/main issues
	plant-based[a]	Global[a]		
Efficiency improvement measures	0-20%	20%	Benefits to high costs	Various measures
Shift to Dry process Pre-Calciner Kilns	20-40%	10-15%	Retrofitting: 50-150 New: benefits to low costs	Compared to wet process
Shift to low carbon fuels	10-20%	15%	25-50	Application depending on availability of NG and competitive use of NG
Application of waste fuels	20-40%	30%	Benefits to small costs	Restricted by availability, quality demands, regulation, standards, public acceptance
Increasing use of additives in cement	0-65%	30-35%	Benefits	Restricted by availability, quality demands, national standards
Alternative cements	n.a.	80%		Limited information available
CO_2-removal	60-65%	-	50-250	Early stage of technology development

a. These percentages may not be add-up. Global technical carbon dioxide emission reduction potential for the options 'dry processes + shift to low carbon fuels + application of waste + increased use of additives' is approximately 60%.

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1. INTRODUCTION

Cement is considered one of the most important building materials around the world. It is mainly used for the production of concrete. Concrete is a mixture of inert mineral aggregates, e.g. sand, gravel, crushed stones, and cement. Cement consumption and production is closely related to construction activity, and therefore to the general economic activity. Cement is one of the most produced materials around the world. Due to the importance of cement as a construction material, and the geographic abundance of the main raw materials, i.e. limestone, cement is produced in virtually all countries. The widespread production is also due to the relative low price and high density of cement, that limits ground transportation because of the relative high costs. Generally, the international trade is limited, when compared to the global production.

Cement production is a highly energy intensive production process. The energy consumption by the cement industry is estimated at about 2% of the global primary energy consumption, or almost 5% of the total global industrial energy consumption [WEC, 1995]. Due to the dominant use of carbon intensive fuels, e.g. coal, in clinker making, the cement industry is also a major emitter of CO_2 emissions. Besides energy consumption, the clinker making process also emits CO_2 due to the calcining process. The cement industry contributes 5% of total global carbon dioxide emissions. Therefore researchers associated with Ecofys Energy and Environment (Netherlands) and Lawrence Berkeley National Laboratory (USA) made for the IEA Greenhouse Gas R&D Programme an assessment to the role of the cement industry in CO_2 production and to carbon dioxide emission reduction options.
In chapter 2 we describe the historical development and global distribution of cement production, we describe the principles of various types of cement production processes, and we give an overview of the emissions from cement production. In chapter 3 options to reduce carbon dioxide emissions from cement productions are discussed. In chapter 4, the development of carbon dioxide emissions are described, following a base line scenario, and two alternative scenarios.

2. CEMENT PRODUCTION

2.1 INTRODUCTION

Cement is an inorganic, non-metallic substance with hydraulic binding properties. Mixed with water it forms a paste, which hardens due to formation of hydrates. After hardening the cement retains its strength. In the common cement types, e.g. Portland, the hardening is mainly due to the formation of calcium silicate hydrates. Cement is made from a mixture of raw materials, which mainly consists of minerals containing calcium carbonate , silicon dioxide, aluminium oxide and iron (III) oxide. These compounds react during a heating process, forming the intermediate 'clinker'. This clinker is ground to a desired fineness together with additives, to form cement. There are numerous different cement types, due to the use of different sources for calcium and different additives to regulate properties. The most important sources for calcium are limestone, blast furnace slag and fly ash. Table 2.1 gives an overview of important cement types. Annex 2 gives an overview of European Cement Standards for 27 types of cement.

Table 2.1. Summary of the main cement types, composition and raw materials needs.

Cement name	Composition	Remarks
Portland[1]	95% clinker 5% gypsum	Gypsum delays setting of the cement. This improves workability
Portland Slag Portland Pozzolana Portland Fly-ash Iron Portland (Germany)	60% clinker 40% slag, pozzolana, fly-ash	
Blast-Furnace	20-65% clinker 35-80% blast-furnace slag	Only granulated high-glass slags can be used, not air-cooled.
Pozzolanic	60% clinker 40% pozzolana	Important in countries with volcanic materials, e.g. Italy, Philippines
Masonry	Mixture of clinker and ground limestone	Binder for brick work

[1] Named 'Portland' because the artificial stone made from the first Portland cement (1824) resembled natural stone from the peninsula Portland.

The exact composition of cement determines its properties, e.g., sulphate resistance, alkali content, heat of hydration, whereas the fineness is an important parameter in the development of strength and rate of setting.

Cement is considered one of the most important building materials around the world. It is mainly used for the production of concrete. Concrete is a mixture of inert mineral aggregates, e.g. sand, gravel, crushed stones, and cement. Cement consumption and production is closely related to construction activity, and therefore to the general economic activity. The 1995 global cement production is estimated at 1453 Million tonnes [Cembureau, 1998], and is one of the most produced materials around the world.

Due to the importance of cement as a construction material, and the geographic abundance of the main raw materials, i.e. limestone, cement is produced in virtually all countries. The widespread production is also due to the relative low price and high density of cement, that limits ground transportation due to the relative high costs. Ground deliveries generally do not exceed distances over 150-200 km. Bulk sea transport is possible, but limited. According to the Global Cement Report, in 1996 global cement trade amounted at about 106 million tonnes of cement, 7% of global cement production. The major cement producers are large countries, e.g. China, India, or regions and countries with a developed economy such as the European Union, U.S. and Japan.

Cement production is a highly energy intensive production process. Clinker production is the most energy intensive production step, responsible for about 70-80% of the total energy consumed [WEC, 1995]. Raw material preparation and finish grinding are electricity intensive production steps. The energy consumption by the cement industry is estimated at 1-2% of the global primary energy consumption [WEC, 1995], or 5% of the total global industrial energy consumption. Cement production emits CO_2 from fuel combustion and calcination. In the calcining process limestone is calcined to calcium oxide, emitting about 0.14 tonne C/tonne clinker. Due to both emission sources, and the emissions from electricity production, the cement industry is a major emitter of carbon emissions, and deserves attention in the assessment of carbon emission reduction options. Due to the widespread production of cement, various technologies used, and the different responsibility and role of industrialised (Annex-I) and developing countries (Non-Annex 1), a geographic analysis is needed.

2.2 HISTORICAL PRODUCTION TRENDS IN THE CEMENT INDUSTRY

Global cement production grew from 594 Mt[1] in 1970 to 1453 Mt in 1995 at an average annual rate of 3.6% [Cembureau, 1998]. Cement consumption and production is cyclical concurrent with business cycles. Table 2.2 provides cement production trends and average annual growth rates for 10 world regions[2] as well as for the 20 largest cement-producing countries. Historical production trends for the

[1] 1 Mt = 1 million tonne = 10^9 kg = 1 Tg

[2] China (including Hong Kong) and India are defined as separate regions due to their size and importance in cement production.

10 world regions are provided in . shows production trends in the 10 largest cement-producing countries from 1970 to 1995.

The regions with the largest production levels in 1995 were China (including Hong Kong), Europe, OECD-Pacific, Rest of Asia, and the Middle East. The largest average annual growth between 1970 and 1995 was seen in the China (12.2% per year), Rest of Asia (7.8% per year), Middle East (7.4% per year), and India (6.6% per year) regions. Growth in Africa (4.5% per year), Latin America (4.1% per year), and OECD-Pacific (3.3% per year) was also relatively high. In contrast, there was very little growth in production in the North America region, and production levels dropped at an average rate of -0.1% per year in Europe during this period. The Eastern Europe/former Soviet Union region showed the largest declines in cement production, averaging –1.3% per year between 1970 and 1995.

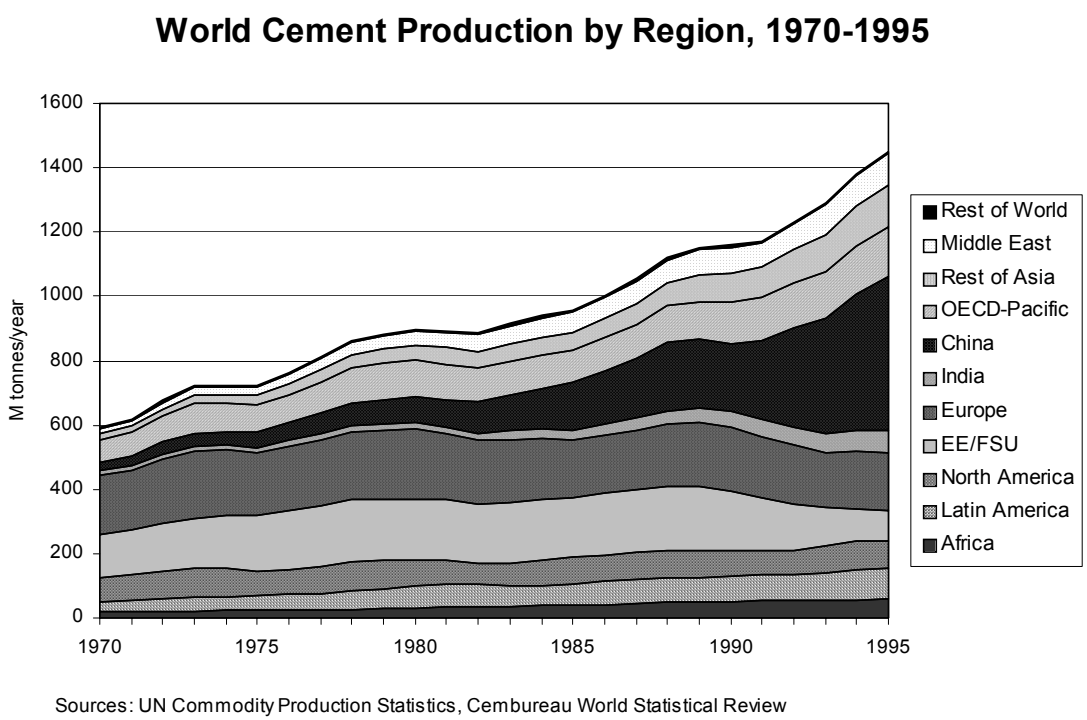


Figure 2.1 Cement Production Trends in Major World Regions, 1970 to 1995. Source: Cembureau, 1998

As a region, *China (including Hong Kong)* clearly dominates current world cement production, manufacturing 477 Mt in 1995, more than twice as much as the next

largest region. Cement production in China (excluding Hong Kong) increased dramatically between 1970 and 1995, growing from 27 Mt to 475 Mt, at an average annual growth rate of 12.2%. Following rapid growth during the period 1970 to 1987, cement production stabilised from 1988 to 1990 due to a combination of economic austerity measures, inflation, and political instability. However, cement production then doubled between 1990 and 1994 due to a construction boom [Sinton, 1996]. Production growth slowed slightly in the 1995-1996 period due to lower demand, surplus in capacity, and low cement prices, but was still estimated to grow to just over 500 Mt by the end of 1997 [Anonymous, 1997b].

Cement production in the *Western Europe region* was relatively stable between 1970 and 1995, with average annual growth of –0.1%. In 1995, production reached 181 Mt. The largest cement-producing countries in this region that year were Italy, Germany (defined as West Germany only to 1990; East and West Germany from 1991 to 1995], Spain, and France. Production in Italy remained relatively stable over the entire period, growing only slightly from 33 Mt in 1970 to a peak of 43 Mt in 1983 and then dropping back down to 34 Mt in 1995. Production in Germany declined almost continuously from a high of 43 Mt in 1972 to a low of 23 Mt in 1985. This was caused by closure of a number of cement plants following an adjustment of the cement industry capacity in response to an evaluation of the long-term outlook [Anonymous, 1986]. Prior to the unification of East and West Germany in 1991, cement production levels in both East and West Germany were dropping at average annual rates of –0.5% and –1.5%, respectively. Following unification, cement production increased at a rapid rate of 5.1% per year. This was mainly due to infrastructure reconstruction in East Germany. Production dropped after 1994 following a drop in construction activities in all areas of Germany and continued declines in demand are expected in the near future [Hargreaves, 1996]. Production grew rapidly in Spain between 1970 and 1980 (9.2% per year on average) as a result of a large investment program encouraged by the Ministry of Industry based on anticipated increases in consumption. The Spanish economy experienced a major recession following the second oil crisis, which lead to a significant decrease in domestic production through 1986. Economic recovery began in Spain in 1986 and cement production increased as a result of increase expenditure on public infrastructure projects. This recovery lasted until 1990, when production dropped again, only to recover in 1994 as Spain's economy once again began to improve after a period of recession. It is expected that cement production will remain at current levels in the medium and long term as Spain slowly constructs new buildings and modernises its infrastructure [Otero, 1997). In France, production declined at an average of –1.4% per year between 1970 and 1995. Recent trends show an even greater decline of –5.2% per year since 1990, although the country's major cement companies are actively pursuing opportunities to export cement to overcome the sluggish domestic market [Hargreaves, 1996].

In 1995, the *OECD-Pacific region* produced 154 Mt of cement, predominately in Japan and South Korea. Average annual growth in this region was 3.3% between 1970 and 1995. Cement production in Japan grew from 57 Mt in 1970 to 91 Mt in 1995. Consolidation of the Japanese cement industry in the 1970s led to an increase in installed capacity as well as cement production. During a period of overcapacity in the early 1980s, a number of obsolete cement plants were closed [Ull-

man, 1991]. Cement production increased beginning in 1987, growing at an average of 5% per year until 1992 when production levels stabilised at about 90 Mt per year. Decreasing demand as a result of an economic recession in Japan led to a reorganisation and rationalisation of the cement industry starting in 1994 in which a number of plants were closed. Domestic production levels are expected to remain relatively constant with fluctuations in total production reflecting varying export levels, which in turn are dependent upon economic conditions in neighbouring Asian countries [Hargreaves, 1996]. South Korean cement production grew at the high rate of 9.4% per year between 1970 and 1995. The most dramatic growth occurred since 1984, when production levels grew from 20 Mt to 55 Mt in 1995, at an average annual growth rate of 10.4%. Much of the growth in cement demand since 1993 was the result of a government economic development plan that encouraged both public and private infrastructure investments in ports, roads, railroads, and subway systems. The recent economic crisis in S. Korea is leading to cutbacks in government spending as well as higher interest rates, both of which will likely slow construction of both infrastructure and housing in the near future [Hargreaves, 1997a].

The *Rest of Asia region* experienced high average annual growth of 7.7% between 1970 and 1995, jumping from production of 20 Mt of cement in 1970 to 130 Mt in 1995. The largest producing countries in this region are Thailand, Indonesia, and Taiwan. Cement production in Thailand grew at a high 10.7% per year on average between 1970 and 1995, but the most dramatic growth occurred since 1986, when production levels jumped from 8 Mt to 34 Mt in 1995 at an average growth rate of over 17% per year. Large infrastructure projects as well as continued growth in residential construction kept demand for cement high since 1995, although the turbulent economic situation may have a dampening effect on both future construction and planned capacity expansion projects in the near future [Hudson, 1997; Hargreaves, 1996]. Thailand is currently operating the world's largest cement kilns. Cement production in Indonesia took off in 1974, climbing at an average annual rate of over 17% until 1995. As with other Asian countries, this growth was fuelled by both infrastructure investments and building construction, mostly in Java that accounted for about 70% of national demand in the early 1990s. Domestic production, which experienced a surplus for export in 1993, was unable to keep up with demand by 1995 and Indonesia began to import cement [Hargreaves, 1996]. Cement production in Taiwan grew at a steady 7.6% per year on average between 1970 and 1993, when production dropped slightly from 24 Mt to 22 Mt in 1995 due to a slowing of the construction boom that started in the early 1990s. Future growth in cement production may continue to be slow due to depletion of a majority of the raw materials near existing plants and resistance to a government plan to relocate cement production to the eastern side of Taiwan [Hargreaves, 1996].

Production of cement in the *Middle East region* also grew rapidly between 1970 and 1995, averaging 7.4% per year. Growth in production slowed slightly since 1990, averaging 4.6% per year through 1995. The largest cement-producing countries in this region are Turkey, Egypt, Iran, and Saudi Arabia. Cement production in Turkey grew at an average rate of 7.0% per year between 1970 and 1995, but slowed slightly since 1993 as the economy suffered from a trade deficit, high pub-

lic debt and inflation. However, the government elected in 1996 is promoting public spending and cement production is forecast to increase in the near future [Hargreaves, 1996]. Cement production growth in Egypt averaged 6.4% per year between 1970 and 1995 slowing to 2.6% per year between 1990 and 1995. Future growth is predicted to be relatively high due to a number of large-scale infrastructure projects including large power stations, subway extensions, new roads, and entire new communities. Annual cement production of between 28 Mt and 32 Mt is projected for the year 2000 [Hargreaves, 1997b]. Cement production in Iran grew at an average rate similar to that of the region, although recent trends show a more pronounced slowing to 2.3% per year between 1990 and 1995. Government financed infrastructure and housing construction projects are leading to large increases in demand which will be met through construction of 21 new cement plants, with a total annual capacity of 30 Mt, by 1999 [Hargreaves, 1996]. In contrast, production in Saudi Arabia showed much higher growth of 13.5% per year between 1970 and 1995 and construction of new plants will increase production capacity to 20 Mt by the late 1990s [Hargreaves, 1996].

Brazil and Mexico dominate production of cement in the Latin American region, which together are responsible for 54% of the production in this region. Brazil experienced rapid growth in cement production between 1970 and 1980, with average increases of 12% per year. In the following decade, Brazil experienced an economic crisis and cement production dropped from 27 Mt in 1980 to 19.5 Mt in 1984, climbing slowly back to 28 Mt in 1995. The slow economic recovery that began in the early 1990s has lead to an upturn in private sector construction, although public sector construction still remained depressed due to Brazil's large public debt [Hargreaves, 1996]. Continued improvement in the economy lead to a jump in production to 34.5 Mt in 1996. Further increases in production are likely, especially in light of the current low per capita consumption levels [Marciano and Kihara, 1997]. Mexican cement production grew from 7 Mt in 1970 to 24 Mt in 1995, at an average annual rate of 5.0%. From 1970 to 1982, Mexico experienced an economic boom due to expansion of its oil production, which in turn financed infrastructure and other construction projects. After the collapse of world oil prices in the mid-1980s, the Mexican economy declined reducing construction activities and cement production. However, the cement industry turned to markets abroad and began exporting to make up for reduced domestic demand. Between 1989 and 1993, cement demand increased again following improvements in the economy. However, the major currency devaluation and subsequent economic crisis in 1994 lead to a dramatic decrease in construction activities and cement production dropped from 30 Mt in 1994 to 24 Mt in 1995. The economic situation improved in late 1995 and cement production levels began to grow again [INEGI, 1998].

In the *Eastern Europe/former Soviet Union region*, cement production grew at an average rate of 2.3% per year between 1970 and 1988. After the break-up of the Soviet Union and the major restructuring that began in that region in 1988, production levels dropped by –12.7% per year on average between 1990 and 1995. Cement production in the former Soviet Union grew steadily from 95 Mt in 1970 to 140 Mt 1989. After the dissolution of the USSR in the late 1980s, production in the region dropped dramatically, falling to 56 Mt in 1995 at an average annual decline of –14.2%. Countries of the former Soviet Union with the highest production

levels in 1995 were the Russian Federation (36 Mt), Ukraine (10 Mt), Uzbekistan (4 Mt), Kazakhstan (1.8 Mt), and Belarus (1.2 Mt). Although Russian economic restructuring is moving slowly and 1996 production levels of 28 Mt were even lower than the previous year [Dutton, 1997], recent growth in construction activities in Russia should lead to increases in cement production levels in the near future [Dutton, 1997]. Production in Belarus is currently unable to meet demand, but should increase slightly over the next few years with completion of a new 1.2 Mt capacity plant. The outlook in Kazakhstan and the Ukraine is much bleaker, with production expected to remain stable or even continue to decline depending upon economic conditions which show "little immediate prospects of improvement" [Hargreaves, 1996]. Unlike the countries of the former Soviet Union, Poland has maintained relatively steady growth in cement production of 0.7% per year between 1970 and 1995, showing high average growth of 3.5% per year between 1990 and 1995.

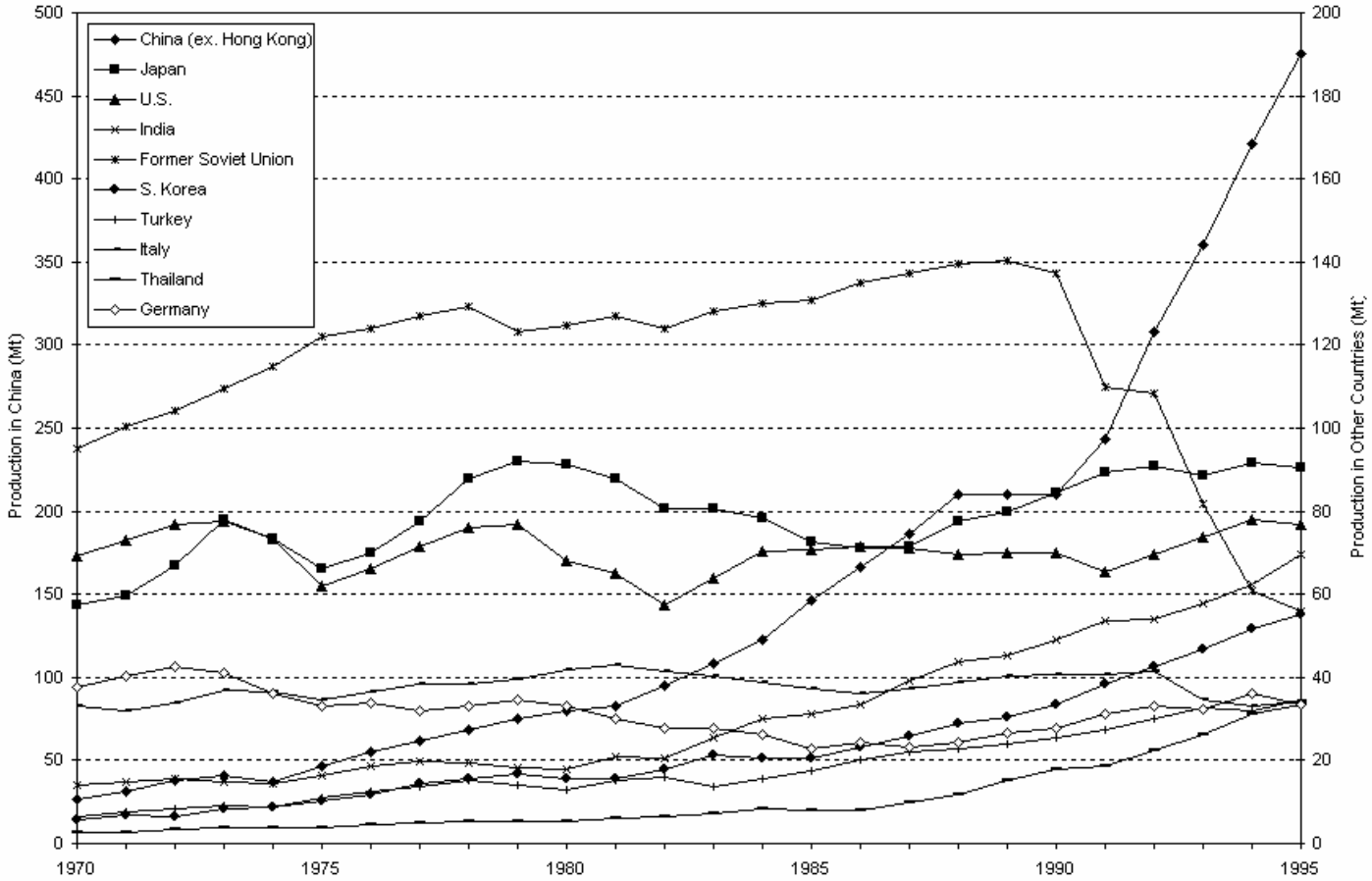
Cement production in the *North American region* was relatively stable between 1970 and 1995, growing only 0.5% per year on average. Production of cement in the United States fluctuated between 58 Mt and 78 Mt, with large drops following the oil price shocks in 1973 and 1979. Similar drops were seen in Japan and, to a lesser extent, Germany during this period. Annual growth, which averaged 0.06% between 1970 and 1990, jumped to 2.4% per year between 1991 and 1995, reflecting an expansion of the U.S. construction industry which is expected to continue through 1999 despite contraction in some areas of the market such as public construction [Hargreaves, 1996]. The U.S. currently is in a situation of domestic under-capacity in terms of cement production and demand is increasingly being met through imports. Since domestic production is at maximum capacity and only a few companies have announced plans to modernise old or build new cement production facilities, it appears that production levels will not climb too rapidly in the near future [Roy, 1998; Hargreaves, 1996].

In the *Indian region*, cement production in India grew from 14 Mt to 70 Mt between 1970 and 1995, at an average annual rate of 6.6%. Growth in production was slower, averaging 3.3% per year, between 1970 and 1982. In 1982, the Indian government began to deregulate the cement industry, allowing companies to establish prices and production volumes [Anonymous, 1998]. As a result, production levels tripled between 1982 and 1995 and average growth reached almost 10% per year. The recent collapse of the coalition government in India coupled with a slowdown in the housing and industrial sectors has lead analysts to project slower growth in the late 1990s, although these projections still have production growing at over 8% per year to the year 2000 [Anonymous, 1998].

The *African region* showed relatively high growth between 1970 and 1995, jumping from 14.5 Mt to 44 Mt at an average annual rate of 4.5%. This growth appears to have slowed recently, increasing an average of 2.7% per year between 1990 and 1995. The largest cement-producing African countries are South Africa, Algeria, and Morocco, although none are among the top-20 cement producing countries worldwide.

Table 2.2 Cement Production Trends and Average Annual Growth Rates for Major World Regions and 20 Largest Cement Producing Countries, 1970-1995 Source: Cembureau, 1998.

	Cement Production						Average Annual Growth	
	1970	1975	1980	1985	1990	1995	1970-1995	1990-1995
Region/Country	Mt	Mt	Mt	Mt	Mt	Mt	%	%
China	26.90	47.48	81.49	147.79	211.15	476.91	12.2%	17.7%
China (excluding Hong Kong)	26.50	46.90	80.00	145.96	209.70	475.00	12.2%	17.8%
Europe	184.61	194.22	223.28	178.04	196.47	180.62	-0.1%	-1.7%
Italy	33.13	34.63	41.93	37.36	40.86	34.21	0.1%	-3.5%
Germany	37.48	32.98	33.14	22.95	27.71	33.30	-0.5%	3.7%
Spain	16.54	24.40	39.63	24.20	28.66	28.49	2.2%	-0.1%
France	29.33	30.66	30.56	23.55	27.05	20.70	-1.4%	-5.2%
OECD-Pacific	68.51	82.55	113.12	99.92	125.79	154.07	3.3%	4.1%
Japan	57.26	66.33	91.15	72.56	84.46	90.59	1.9%	1.4%
South Korea	5.82	10.13	15.57	20.50	33.58	55.13	9.4%	10.4%
Rest of Asia	20.08	30.55	48.77	57.16	88.67	130.09	7.8%	8.0%
Thailand	2.63	3.99	5.30	7.91	18.04	33.65	10.7%	13.3%
Indonesia	0.56	1.09	5.83	9.61	15.78	23.25	16.1%	8.1%
Taiwan	4.54	6.80	14.06	13.56	18.40	22.41	6.6%	4.0%
Middle East	19.31	29.28	44.25	74.85	92.76	116.29	7.4%	4.6%
Turkey	6.37	10.89	13.01	17.67	25.38	34.75	7.0%	6.5%
Egypt	3.69	3.59	3.11	5.28	15.15	17.22	6.4%	2.6%
Iran	2.58	5.00	8.00	12.46	15.06	16.85	7.8%	2.3%
Saudi Arabia	0.67	1.13	2.91	9.85	11.49	15.77	13.5%	6.5%
Latin America	35.62	52.46	75.57	71.25	82.44	97.28	4.1%	3.4%
Brazil	9.00	16.74	27.19	20.64	25.85	28.26	4.7%	1.8%
Mexico	7.18	11.61	16.26	20.68	23.83	24.20	5.0%	0.3%
Eastern Europe/former Soviet Union	134.13	177.23	189.53	189.62	189.71	96.25	-1.3%	-12.7%
Former Soviet Union	95.23	122.04	124.80	130.77	137.35	56.05	-2.1%	-16.4%
Poland	12.18	18.54	18.44	14.86	12.36	14.65	0.7%	3.5%
North America	76.34	72.69	79.24	80.86	81.04	87.51	0.5%	1.5%
U.S.	69.05	61.82	68.24	70.67	69.95	76.90	0.4%	1.9%
India	13.99	16.21	17.76	31.15	48.90	69.57	6.6%	7.3%
Africa	14.53	19.60	28.36	34.58	38.45	43.94	4.5%	2.7%
World	594.03	722.26	901.36	965.21	1155.72	1452.53	3.6%	4.7%



Source: Cembureau, 1998

Figure 2.2 1970-1995 Cement Production Trends in the 10 Largest Cement-Producing Countries in 1995 (China only on left-hand axis).

2.3 CEMENT PRODUCTION PROCESS DESCIPTION

Four production steps are distinguished in the description of the production of cement:

- Quarrying and mining: mining of the raw materials.
- Preparing raw materials: Mixing/homogenising, grinding and preheating (drying) produces the *raw meal*.
- Burning of raw meal to form cement clinker in the kiln: The components of the raw meal react at high temperatures (900-1500 °C) in the rotary kiln, to give clinker.
- Finish grinding of clinker and mixing with additives: After cooling the clinker is ground together with additives.

In this chapter these steps will be subsequently described. In Figure 2.4 the main steps in the process of cement making are depicted.

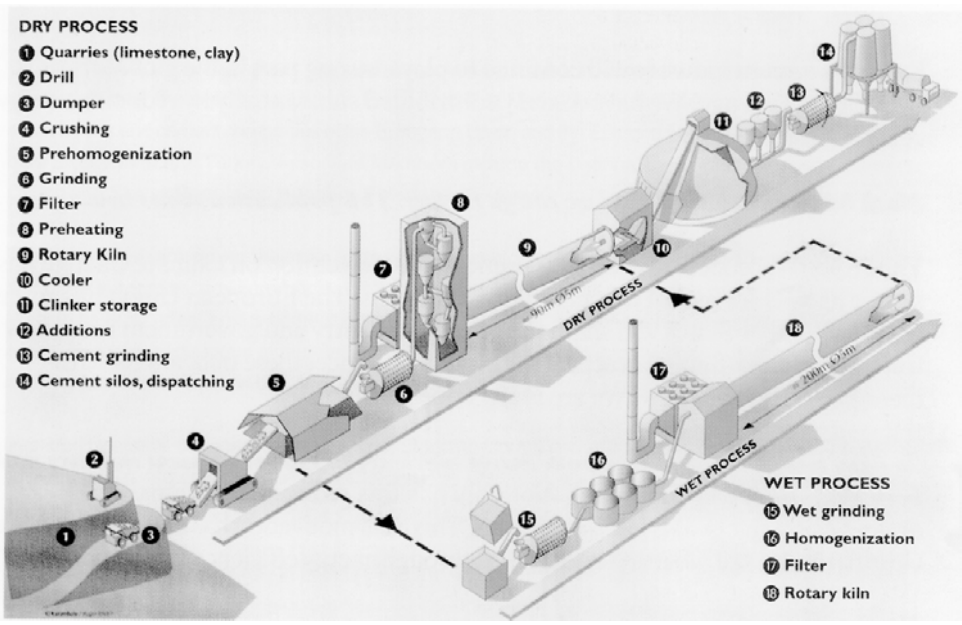


Figure 2.3. Main cement production steps [source Cembureau,1998b]

2.4 RAW MATERIALS

The most common raw materials used for cement production are limestone, chalk and clay. Limestone and chalk provide the required calcium oxide and clay provides the silicon, aluminium and iron oxides. It is often necessary to raise the content of silicon oxides and iron oxides by adding quartz sand and iron ore. An exact and constant composition of the raw materials is very important for the quality and uniformity of cement [Fog and Nadkarni, 1983]. As limestone is the main calcium source worldwide, in the following description we will use limestone as the repre-

sentative raw material, and we will indicate differences with respect to other materials where important.

The most common raw materials used for cement production are limestone, chalk and clay, although more than 30 raw materials (many trace elements from the earth's crust) can be used (Greer *et al*, 1992). Most commonly the main raw material, the limestone or chalk, is obtained from local quarries. (Limestone and chalk provide the required calcium oxide and clay provides the silicon, aluminium and iron oxides required for Portland cement). The limestone and chalk are most often extracted from open-face quarries but underground mining can be employed (Greer *et al*., 1992). The collected raw materials are selected, crushed, ground, and proportioned so that the resulting mixture has the desired fineness and chemical composition for delivery to the pyro-processing systems (Greer *et al*, 1992). It is often necessary to raise the content of silicon oxides and iron oxides by adding quartz sand and iron ore. The excavated material is transported to a crusher. A jaw or gyratory crusher, a roller or hammer mill is used to crush the limestone. The crushed material is screened, and stones are removed. At least 1.5-1.75 tonnes of raw material are required to produce one tonne of Portland cement (Greer *et al*, 1992; Alsop and Post, 1995), depending on fuel ash content and dust losses.
The energy consumption for transport in the quarry is estimated at 18 MJ/tonne limestone and for blasting at 1.3 MJ/tonne lime stone [Heijningen, 1992]. With a limestone consumption of 1.2 tonnes per tonne clinker the total energy use for blasting and transport is estimated at 23 MJ/tonne clinker.
Table 2.3. summarises the energy consumption of the main crushers, as given by Duda [1985].

Table 2.3. Energy consumption of various crusher types. Source: Duda [1985].

Crusher Type	**Power Consumption (kWhe/tonne material input)**
Jaw Crusher	0.3 - 1.4
Gyratory Crusher	0.3 - 0.7
Roller Crusher	0.4 - 0.5
Hammer Crusher	1.5 - 1.6
Impact Crusher	0.4 - 1.0

The raw materials are further processed and grinded. The grinding differs with the pyro-processing process used. The raw materials are prepared for clinker production either by dry or wet processing. In dry processing, the materials are ground in ball mills or in roller mills. In a ball (or tube) mill, steel balls in are responsible for decreasing the size of the raw material pieces in a rotating tube. Rollers on a round table fulfil this task of comminution in a roller mill. When raw materials contain more than 20% water, wet processing can be preferable[1]. In the wet process the slurry typically contains 38% water (range of 24-48%). The raw materials are then processed in a ball mill to form slurry (with extra water). Various variants exist, e.g. semi-wet (moisture content of 17-22%) and semi-dry (moisture content of 11-14%) to reduce the fuels consumption in the kiln. The moisture content in the (dried) feed of the dry kiln is typically around 0.5% (0 - 0.7%). The feed to the kiln

[1] Originally, the wet process was the preferred process, as it was easier to grind and control the composition and size distribution of the particles in a slurry. The need for the wet process was reduced by the development of improved homogenization processes

is called 'raw meal'. Approximately 1.65-1.75 tonnes of raw meal are needed for the production of one tonne clinker [Alsop & Post, 1995].

Table 2.4. Energy consumption of raw meal grinding. The electricity consumption includes the mill drives and mill fans. Typical fan power use varies between 5 and 8 kWhe/tonne [CowiConsult, 1992].

Mill Type	Typical power consumption (kWhe/tonne input)
Ball mill	22
Vertical mill	16
Hybrid systems	18-20
Roller press - integral	12
Roller press - pregrinding	18

2.5 CLINKER PRODUCTION

Clinker is produced by pyro-processing. The raw meal is burned at high temperatures, first calcining the materials followed by clinkerization to produce clinker. Various kiln types have been used historically or are used around the world. Besides the rotary kiln, the vertical shaft kiln is used, mainly in developing countries. Especially China and India are large users of shaft kilns, as transport problems limit the distribution of raw materials and cement. In China, by far the largest cement producer in the world, alone, it is estimated that over 3000 shaft kilns are operated with typical capacities of 200 tonnes per day [Vleuten, 1994]. First we will describe the theoretical energy requirements for cement making. Then, we will describe the rotary kiln types, followed by a description of the shaft kilns. We will first discuss the general trends in kiln types and development, followed by a brief description of the main kiln types. The technical description of the process includes discussion of typical energy use and emissions for the main kiln types.

2.5.1 Theoretical Heat Requirements for Clinker Making

The enthalpy of formation of 1 kg Portland cement clinker is calculated to be about 1.76 MJ [Taylor, 1992]. This calculation refers to reactants and products at 25 °C and 0.101 Map. The enthalpy changes at the temperatures at which the reactions occur are somewhat different. A reasonable range for ΔH of the formation of 1 kg Portland cement clinker is 1.75 ± 0.1 MJ [Taylor, 1992]. Figure 2.5 shows the most important processes that contribute to the clinker formation and to what extent they determine the theoretical heat requirement.

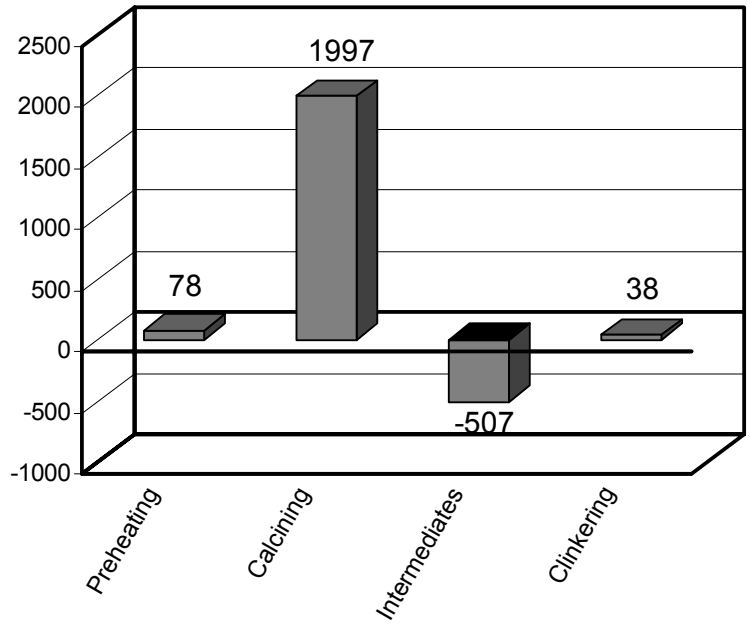


Figure 2.4. Theoretical energy requirements (in MJ/kg clinker) for the various chemical reactions in clinker making.

Additional to the theoretical minimum heat requirement energy is required to evaporate water and to compensate for the heat losses. Heat is lost from the plant by radiation or convection, and with clinker, emitted kiln dust and exit gases leaving the process.

Table 2.5. Typical energy requirement of dry and wet clinker production [Taylor, 1992].

Heat requirement (MJ/kg clinker)	Dry process	Wet Process
ΔH chemical reactions	1.8	1.7
Evaporation of water	0.0	2.4
Heat lost in exit gases and dust	0.6	0.8
Heat lost in clinker	0.1	0.1
Heat lost in air from cooler	0.4	0.1
Heat lost by radiation and convection	0.3	0.7
Total	**3.3**	**5.7**

Table 2.5 gives an indication of the most important energy losses in cement manufacturing. Approximately 1.5-1.6 MJ heat is lost in both processes with exit dust and exit gases, clinker, cooling air, and through radiation and convection.

2.5.2 Clinker burning

The ground raw meal is fed into a kiln and heated slowly to a temperature of 1450 °C. The heating process takes 40 minutes to 5 hours, depending on kiln type. After

10-20 minutes at 1450 °C, the mixture is cooled while leaving the kiln. The following processes take place in the kiln [Alsop and Post, 1995; Taylor, 1992]:

100 °C	The mixture loses liquid water
100-600 °C	Adsorbed and chemically bound water is released. Recrystallization of dehydrated clay
700-1300 °C	Decomposition of calcite: $CaCO_3 \rightarrow CaO + CO_2$ The reaction proceeds very rapidly at temperatures above 900 °C. Decomposition of clay minerals Reaction of decomposition products to give belite, aluminate and ferrite. The material loses more than a third of its dry weight during this stage.
1280-1450 °C	Formation of a melt, mainly from aluminate and ferrite. At 1450 °C, 20-30% of the mix is liquid. The material sticks together and forms nodules (clinker). Belite and lime react in the presence of melt, to give alite.

The clinker must be cooled rather rapidly, because slow cooling yields less tricalcium silicate (alite). This is due to the possible reaction of alite with the melt to form dicalcium silicate (belite) and calcium oxide, which is then consumed in the formation of tricalcium aluminate (aluminate). Alite is, however, very important for the hardening properties of the cement. Therefore, fast cooling should prevent the unwanted reaction as much as possible. Cement clinker consists of the compounds given in Table 2.6.

Table 2.6. Typical composition of cement clinker.

Compound	**Chemical formula**	**Content (wt%)**		
		min.	average	max
Tricalcium silicate (Alite)	$3\ CaO.SiO_2$	45	62	75
Dicalcium silicate (Belite)	$2\ CaO.SiO_2$	5	15	35
Calcium aluminoferrite (Ferrite)	$4\ CaO.Al_2O_3.Fe_2O_3$/ $6\ CaO.2\ Al_2O_3.Fe_2O_3$	4	8	15
Tricalcium aluminate (Aluminate)	$3\ CaO.Al_2O_3$	4	11	15
Free Calcium oxide	CaO	0.1	1	4
Free Magnesium oxide	MgO	0.5	1.5	4.5

Vertical shaft kilns for clinker production have been in use since the invention of Portland cement in 1824. The intermittent operation was a disadvantage, leading to a extremely high energy consumption. Continuous production of clinker started with the use of shaft kilns around 1880, followed by the introduction of the dry rotary kiln. The wet process, fed by slurry, was introduced to achieve better homog-

enisation of the kiln feed, easier operation, less dust, and more uniform cement quality. In 1928 the Lepol, or semi-dry, process was introduced, reducing moisture content of the material entering the kiln, reducing fuel consumption. Improved raw meal homogenisation systems and dust collection equipment improved the product quality of the dry process. The original long dry kiln, e.g. used in the U.S., was relatively inefficient, due to high energy losses. In the U.S. more recent dry kilns have been able to achieve higher energy efficiencies of up to 3.6 GJ/tonne. The introduction of a dry kiln with material (suspension) preheating reduced the energy costs compared to the commercially used processes in the 1950's. The latest technology development was the introduction of the precalciner in the 1970's; reducing energy needs further, while boosting productivity when rebuilding existing kilns.

2.5.3 Rotary Kilns

In industrialised countries, the ground raw materials are predominantly processed in rotary kilns. A *rotary kiln* is a tube with a diameter up to about 6 meter. The tube is installed at an angle of 3-4° with the horizontal, and rotates at 1-4 times per minute. The ground raw material moves down the tube toward the flame. In the sintering (or clinkering) zone the combustion gas reaches a temperature of 1800-2000 °C, the material 1350-1500 °C. The length of a long kiln is 32-35 times its diameter. The longest kilns have lengths of up to 230 meter. The length of a short (dry) kiln is 11-20 times its diameter.
The kiln is equipped with a preheater, in which the raw meal is preheated with waste heat from the kiln, before entering the kiln. Introduction of a preheater reduces the energy requirement of the burning process. A preheater that is especially applicable to the dry process is the *suspension preheater*. It consists of various cyclone stages (2-6), that are arranged above each other in a tower, 50-120 m high. The raw materials are preheated to 800-900 °C. The exhaust gas leaving the uppermost cyclone has a temperature of about 380 °C in a precalciner kiln. The suspension preheater can be used to dry raw material with up to 12% moisture. Another preheater is the *grate preheater*. Pellets or briquettes, pressed of raw material slurry, are placed on a grate that travels through a closed tunnel. This tunnel is divided in a drying chamber and a hot gas chamber. The exhaust gas of the kiln enters the preheater in the hot gas chamber with a temperature of 1000-1100 °C, where it cools down to 250-300 °C. It leaves the drying chamber at 90-150 °C. The raw material reaches a temperature of 150 °C in the drying chamber and 700-800 °C in the hot gas chamber. Additionally a *precalciner* can be integrated between the kiln and the suspension preheater. This is a chamber with a burner, in which 80-95% of the $CaCO_3$ can be dissociated before entering the kiln. In processing without precalcination, the decomposition (calcination) of $CaCO_3$ to CaO and CO_2 takes place in the kiln. Application of a precalcinator allows a shorter kiln and can reduce energy consumption by 5 to 10 %, by reducing radiation losses of the kiln [Duda, 1985]. About 60-70 % of the fuel is burned in the precalcinator, 30-40% in the kiln.

Cooling of the clinker can be performed in a grate cooler, a tube (rotary) cooler or a planetary cooler. In a *grate cooler* the clinker is transported on a moving or reciprocating grate, passed by a flow of air. In a *tube or planetary cooler* the clinker is cooled in a countercurrent air stream. The cooling air reaches a temperature of

800-900 °C in an efficient kiln. It flows into the rotary kiln, serving as combustion air. The largest part of the energy contained in the clinker is returned to the kiln in this way. With grate coolers there is more cooling air available then is required for combustion. The excess air is used for drying of raw material, or vented through a dust filter.

Figure 2.6 gives an overview of the heat requirements of different kiln types [Duda, 1985]. Table 2.7 shows the sensitivity of the fuel consumption of a rotary kiln with a 4 stage preheater to changes in energy losses in different parts.

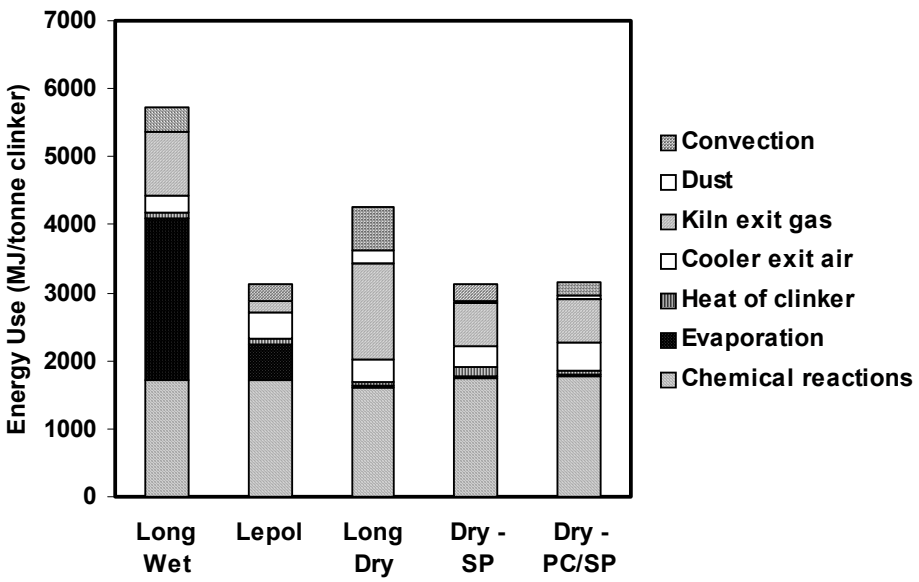


Figure 2.5. Energy consumption and losses in the major kiln types (wet process, Lepol or semi-wet, long dry, dry process with four stage suspension preheating, and dry process with four stage suspension preheating and precalcining). Based on data given by Vleuten [1994].

Table 2.7. Sensitivity of fuel consumption to changes in energy losses in different parts of rotary kiln [Scheuer and Sprung, 1990].

Energy loss	$d_{fuel\ consumption}/d_{energy\ loss}$
Waste gas	0.87
Wall cyclone – stage 1	0.22
- stage 2	0.44
- stage 3	0.76
- stage 4	1.18
Kiln wall	1.18
Theoretical heat requirement	1.18
Cooler	1.46

Improvement of cooler efficiency has the most pronounced effect on energy consumption of the kiln. A modern dry kiln with a diameter of 5 m and a length of 55 m, equipped with a 4 stage preheater and a precalciner, has a heat requirement of 2.9 MJ/kg clinker [Anonymous, 1994]. Compared to a theoretical heat requirement of 1.76 MJ/kg, this kiln has an efficiency of 60%.

If excess alkali, chlorides or sulphur are present in the kiln feed and/or fuel, these might vaporise in the kiln and condense in the preheater. This can lead to build-up in the equipment (leading to operating problems). Especially in the US and Canada low alkali cements are demanded by the sector, more than in e.g. Europe [Holderbank, 1993]. Removing clinker kiln dust (CKD) from the process is a means of reducing the concentration of alkali, chlorides and sulphates in the clinker. In wet and long dry kilns, alkali salts tend to concentrate in the fine particles captured in exhaust gas dust control equipment. By disposing of part of this captured dust, the amount of alkalis in the kiln system can be controlled. In the case of the preheater/precalciner kilns, particularly when the exhaust gases are used to dry the raw meal in in-line raw mills, alkali-rich material must be extracted by means of bypass, which diverts part of the exhaust gas flow and removes the particulates from it for disposal. Typically, the bypass takes 10-70% of the kiln exhaust gas. It is essential to keep the extracted gas volume with the extraction of the volatiles at a minimum to reduce the heat losses. The heat losses are typically estimated at 8-20 kJ/kg clinker per %-bypass, for pre-calciner or preheater kilns respectively [Alsop and Post, 1995].

Power consumption for a rotary kiln is comparatively small, and generally around 17 and 23 kWh/tonne clinker (including the cooler and preheater fans) [CowiConsult, 1992]. The power consumption of the cooler varies between 9 and 12 kWh/tonne clinker for a planetary and a grate cooler respectively [CowiConsult, 1992]. A grate cooler recovers more heat from the clinker. A kiln equipped with cyclone or suspension pre-heaters also uses electricity for the cyclones and fans, as do the fans for the alkali bypass to produce low-alkali cements. The typical power consumption of a four stage suspension preheater kiln is estimated at 20-23 kWh/tonne clinker [Duda, 1985]. For the production of low-alkali cements a bypass fan is needed, consuming approximately 2 kWh/tonne clinker [Heijningen, 1992]. The total power consumption in the clinker kiln is hence estimated at typically 23-25 kWh/tonne clinker. Some power is used for internal transport and utilities.

Wet Rotary Kiln. In the wet kiln, the raw meal typically contains approximately 38% moisture. The wet slurry was produced because the meal homogeneity was easier to control. Therefore, the wet process needs less electrical energy (typically between 10 and 12 kWh/tonne) [CowiConsult, 1992] as the raw meal grinding requires less energy. The wet process is still a viable technology for specific raw materials, e.g. those with high moisture content (15-25%) like chalk (used in e.g. the United Kingdom). The need to reduce fuel costs and the greater tolerance of the wet process to alkali, chlorides and sulphates than kilns equipped with preheaters has lead to considerable use of waste fuels in wet process kilns. The water is first evaporated in the kiln in the low temperature zone. The evaporation step made a long kiln necessary. The length to diameter ratio may be up to 38, with lengths up

to 230 meter. The capacity of large units may be up to 3600 tonnes of clinker per day. Fuel use in a wet kiln may vary between 5.3 and 7.1 GJ/tonne clinker [Cowi-Consult, 1992; Vleuten, 1994]. The variation is due to the energy need for the evaporation, and hence the moisture content of the raw meal. The evaporation energy needed may vary between 1.8 and 3.0 GJ/tonne clinker [CowiConsult, 1992].

Lepol Rotary Kiln. The Lepol uses waste heat to preheat the raw meal. As such it may be seen as a semi-dry process (see below). The first Lepol Kiln using a grate preheater was constructed in 1928, and the process was commercialised after the second world war [CowiConsult, 1992]. The preheater consists of two chambers; a hot gas chamber and a drying chamber. The raw meal travels through the preheater on a travelling grate. Fans draw the exhaust gas from the kiln into the top of the preheater. The exhaust air travels through the granules bed, and is (after dedusting) lead to the second, drying, chamber. The preheating may lead to high alkali contents in the processed raw meal due to the temperatures below 900 ºC, leading to condensation of the alkali metals [Crosilla and Häutle, 1997]. The Lepol Kiln can have a substantially lower fuel consumption compared to the wet process, i.e. approximately 3.5-3.6 GJ/tonne clinker [CowiConsult, 1992; Crosilla and Häutle, 1997]. The power consumption is 32 kWh/tonne clinker [Crosilla and Häutle, 1997].

Semi-Wet Rotary Kiln. In the semi-wet process the wet slurry is processed in filter presses (after the grinding) to reduce the moisture content. The filter press has a power consumption of typically 3 to 5 kWh/tonne clinker [CowiConsult, 1992]. The semi-wet process was introduced in the early 1960's as an improvement to the wet process. It is mainly used to modify existing wet kilns. The fuel savings are roughly estimated at 200-300 MJ/tonne clinker [CowiConsult, 1992]. The moist cake (approximately 20% moisture content) can be further dried in a grate preheater, and is called a semi-wet grate preheater kiln [Vleuten, 1994].

Semi-Dry Rotary Kiln. In the semi-dry kiln, waste heat recovered from the kiln is used to reduce the moisture content of the raw meal. The semi-dry process is in many ways similar to the Lepol-process. The pelletised dried meal, or cake, then fed to the kiln. Two-stage suspension preheating (see below) can be used to convert a wet process kiln, reducing fuel consumption.

Dry Rotary Kiln. The first development of the dry process took place in the U.S. and was a long dry kiln without preheating, or with one stage suspension preheating. The energy consumption of these processes was still high. Heat transfer was improved by using chains in the kiln. The development of the suspension preheater (i.e. a cyclone) in the 1930's increased the heat recovery, and a small degree of pre-calcination, due to the high particle surface area. Preheating is also possible by using a shaft preheater (and a cyclone for dedusting). Shaft preheaters are still used if raw material properties determine so, because shaft preheaters are less vulnerable to build-up of volatiles and alkalis.

Dry Rotary Kiln with suspension preheating. In this process multi-stage preheating is accomplished by various cyclones and riser ducts in series. The raw

meal travels through the cyclones, in each following cyclone the pre-heating temperature is higher. The cyclones are hanging in a 50-120 meter high tower. Four-stage preheating was the standard technology in the 1970's, while today five and six stage preheater kilns are constructed. A six stage preheating is only possible if the raw materials have a low moisture content, reducing the need for low temperature waste heat for drying the raw materials. The preheating allows a shorter kiln, with length/diameter ratio typically between 13 and 16. Due to alkali build-up at lower temperatures in the cyclones a by-pass of exhaust gas of the kiln may be needed to reduce the alkali burden of the gas. This leads to extra power use (for the by-pass fan) of approximately 2 kWh/tonne clinker and heat losses varying with the by-pass level. The by-pass level may vary between 10 and 70% [Alsop and Post, 1995]. The alkali content in the clinker influences the setting properties of the cement and the strength, as well as long-term performance due to expansive reaction with certain types of aggregates. In the U.S. and Canada typically lower alkali contents are demanded by cement buyers [Holderbank, 1993]. The typical fuel consumption of a dry kiln with 4/5-stage preheating may vary between 3.1 and 3.5 GJ/tonne clinker [CowiConsult, 1992]. A six stage preheater kiln may theoretically use as few as 2.9-3.0 GJ/tonne clinker [Vleuten, 1994].

Dry Rotary Kiln with pre-calcination and preheating. The technology of pre-calcining has been developed in Germany and Japan in the early 1970's, but is now commercially available from various suppliers. In a precalciner kiln a second combustion chamber has been added to a conventional suspension preheater. The preheated feed enters the pre-calciner, where 80-90% of the feed is calcined. The pre-calcined feed is then fed to the kiln. This reduces the kiln energy requirements by 3-8% [CowiConsult, 1992] compared to that of a four stage preheater kiln. Advantages of the precalciner kiln are the possibility to bypass flue gases without large energy losses [Vleuten, 1994] and the possibility of using low-grade fuels in the calciner. As much as 60% of the fuel input may be used in the precalciner. As the operating temperature in the pre-calciner is much lower, low-grade fuels can be used. The lower operating temperature also reduces the NO_x emissions from a pre-calciner kiln, also when using alternative fuels like plastics [Conroy, 1997; Tokheim, 1998]. Another major advantage is the possibility to increase the capacity of the kiln, as much of the material is already calcined when entering the kiln, or to construct shorter, less capital intensive, kilns with a length/diameter ratio of 10-12 [KHD proceedings]. Large preheater/precalciner kilns are operating around the world, with the largest up to 12.000 tonnes of clinker per day [Siam City Cement, Thailand]. The most efficient SP/PC kilns use approximately 2.9 GJ/tonne clinker [Anonymous, 1994, Somani, 1997; Su, 1997]. Long-run operational results may be a little higher due to production and maintenance stops. Almost all new constructed kilns around the world are SP/PC kilns. The current share of SP/PC kilns varies widely from country to country.

2.5.4 Shaft Kilns

Shaft kilns are used in countries with a lack of infrastructure to transport raw materials or cement, or for the production of speciality cements [Rajbhandari, 1995]. Today, most vertical shaft kilns can be found in China and India. In these countries the lack of infrastructure, lack of capital and power shortage favoured the use of

small-scale local cement plants. In China this is also the consequence of the industrial development pattern where local township and village enterprises (TVEs) have been engines of rural industrialisation, leading to a substantial share of shaft kilns in the total cement production. Regional industrialisation policies in India also favoured the use of shaft kilns other than the large rotary kilns in major cement producing areas. In India shaft kilns represent a growing part of total cement production, and established almost 10% of the 1996 production capacity [Hargreaves, 1998]. In China the share is even higher with an estimated 87% of output in 1995 [Peikang, 1997], although the share seem to be reduced due to construction of new rotary kilns in China. Typical capacities of shaft kilns vary between (fully hand operated) 30 and (mechanized) 180 tonnes of clinker per day [Feng *et al*, 1995]. Shaft kilns may produce a poor quality clinker, as it is more difficult to manage all process parameters.

We base the process description on Chinese technologies, as they are the most widely used. The principle of all shaft kilns is similar, although design characteristics may vary. The shaft kiln is most often cone-shaped. The pelletized material travels from top to bottom, through the same zones as a rotary kiln. The kiln height is determined by the time needed for the raw material to travel through the zones, and by operational procedures, pellet composition and air blown [Feng, 1995]. The preheating zone (on top) is equal to approximately 5% of the height, the calcination zone 10% and the cooling zone approximately 85% [Feng *et al*, 1995]. Shaft kilns can reach a reasonably high efficiency through the good interaction with the feed and low energy losses through exhaust gases (counterflow) and radiation. Fuel consumption in China may vary between 3.7 and 6.6 GJ/tonne clinker for mechanised kilns, with the average estimated at 4.8 GJ/tonne clinker [Feng *et al*, 1995]. In India, presumably, shaft kilns may use between 4.2 and 4.6 GJ/tonne clinker, although lower figures have been reported in the literature [Vleuten, 1994]. The largest energy losses in shaft kilns may be due to incomplete combustion, resulting in emissions of CO and VOCs to the environment. Electricity use in shaft kilns is very low.

In Table 2.8 we summarise the main process characteristics and performance of the main kiln types.

Table 2.8. Summary table of the main production processes. Main process characteristics, energy use and emissions are given (expressed per metric tonne of clinker).

	Rotary Kilns						**Shaft Kiln** (China)
	Wet	Lepol	Semi-wet	Long dry	Short dry kiln Suspension Preheating	Short dry kiln Preheating/ precalcining	
Capacity range							
Fuel use (GJ/tonne)	5.9	3.6		4.2	3.3 - 3.4	2.9 - 3.2	3.7 - 6.6
Power use kiln (kWh/t)	25	30		25	22	26	
Primary energy[1]	6.2	3.9		4.5	3.5 - 3.7	3.2 - 3.5	
CO_2 emissions (tC/t)[2]	0.2-0.3						
SO_2 emissions (kg/t)[3]	1.6 – 6.0						
NO_x emissions (kg/t)[4]	0.8 – 4.0						
Dust (PM) emissions (kg/t)[5]	0.05 – 0.26						
Capital costs (US$/t)[6]							320 Yuan[8]
O&M costs (US$/t)[7]							

1. Assuming a 33% electricity generation efficiency
2. Assuming 100% use of coal as kiln fuel and an emission factor of 0.22 kg C/kWh [Faaij, 1995]. The carbon emissions due to calcination of limestone is estimated at 570 kg CO_2/tonne clinker
3. The sulphur emissions strongly depend on the raw materials and fuels used, the amount of fuels used, as well process lay-out [Van Kuijk, 1997]. Sulphur emissions are affected by local air pollution legislation. For example, the US EPA emission standard for the year 2000 limits the sulphur emissions to 0.517 kg SO_2/GJ-fuel used [Holderbank, 1993]
4. The NO_x emissions depend strongly on the process conditions. Large differences exist between individual kilns. Therefore, key figures for untreated emissions from clinker plants can not be established easily [Van Kuijk, 1997]
5. Dust (or particulate matter) emissions are mainly from grinding and may vary [Van Kuijk, 1997]
6. The costs may vary widely for different countries and local conditions. The capital costs of a new greenfield clinker plant in Canada are estimated at 175-250 C$/tonne capacity [Holderbank, 1993]
7. The operating costs vary widely due to the differences in labour costs, age and plant type. An overview of U.S. cement plants estimates the operating costs at 36.4 US$/tonne cement in 1990 (including costs for power, fuel and raw materials) [Huhta, 1992].\
8. Due to non-market conform currency rate this amount is given in the Chinese currency yuan.

2.6 GRINDING CEMENT CLINKER

After cooling the clinker is stored in the clinker silo or other storage equipment. To produce powdered cement, the nodules of cement clinker leaving the kiln are ground. Grinding of cement clinker, together with additives to control the properties of the cement (e.g. fly ash, blast furnace slag, pozzolana, gypsum and anhydrite) can be done in ball mills, roller mills, or roller presses. Combinations of these milling techniques are often applied. The most common types are listed in Table 2.9. Coarse material is separated in a classifier to be returned for additional grinding. Power consumption for grinding depends strongly on the fineness required for the final product and the additives used (in intergrinding). The fineness of the cement influences the cement properties and setting time. The required fineness may vary within and between countries depending on the standards for cement. In Table 2.9 we will give the specific power consumption for grinding cement to a fineness of 4000 Blaine. Grinding of blast furnace slag requires more power, i.e. between 50 and 70 kWh/tonne [Cowiconsult, 1992]. Finished cement is stored in silos, tested and filled into bags, or loaded on trucks or other forms of bulk transport.

Table 2.9. Power consumption for 4000 Blaine Portland cement, containing 95% clinker and 5% gypsum [CowiConsult, 1992].

Mill Type	Power Consumption (kWh/tonne)			
	Ball Mill	Separator	Roller Press	Total
Ball Mill	55	0	0	55
Ball Mill with separator	43	4	0	47
Roller press/ball mill/separator	31	4	6	41
Roller press/Separator/ball mill	22	6	11	39
Roller Press with separator	0	7	21	28

The roller press is a relative new technology, and is more common in Western Europe than in other regions, e.g. North America [Holderbank, 1993]. Various new grinding mill concepts are under development or demonstrated [Seebach, 1996], e.g. the Horomill [Buzzi, 1997], Cemax [Folsberg, 1997], and the IHI mill.

Additional Power Consumption

Additional power is consumed for conveyor belts and packing of cement. The total consumption for these purposes is generally low and not more than 5% of total power use [Vleuten, 1994]. Total power use for auxiliaries is estimated at roughly 10 kWh/tonne clinker [Heijningen, 1992]. The power use for conveyor belts is estimated at 1-2 kWh/tonne cement [Cowiconsult, 1992]. The power consumption for packing depends on the share of cement packed in bags. In Europe a relative large share of cement is shipped from the plant in 25 kg or 50 kg bags (19%) compared to the U.S. (5%) or Canada (8%) [Holderbank, 1993].

2.7 HISTORICAL TREND IN ENERGY USE

In Europe, since the 70s, the energy required to produce cement clinker has fallen about 30%. In 1970 the average energy use in the cement production process in

Europe amounted to about 4.8 MJ per kg clinker, which gradually reduced to 3.7 MJ/kg in 1990. Since then, the average energy use remained constant. According to Cembureau [1998b], this was caused by the fact that the limit of available technical means had been reached. The reduction has been made, amongst others, through voluntary agreements [Cembureau, 1998b].

- France: between 1990 and 2000 reduce fossil fuel CO_2 by 25% and CO_2 emissions per kg of cement by 10%
- Germany: between 1987 and 2005: reduce specific fuel consumption by 20%;
- The Netherlands: between 1989 and 2000: reduce energy efficiency index by 21%.

In the US, due to relative high prices of petroleum products and natural gas the cement industry shifted away from these fuels to coal and petroleum coke, accounting in 1994 for more than 75% of kiln fuel in the US. Cement manufacturing has an advantage over other industries in using coal and petroleum coke. The fact that the fuel is burned inside the kiln means that coal ash is trapped by the material in the kiln and becomes incorporated in the clinker resulting in slightly higher production. The primary reason of the growth of the use of petroleum coke is its high sulphur content, typically ranging from 3 to 5%, making it unattractive for many fuel applications. However, the presence of limestone and free lime in the kiln effectively scrub the SO_2 generated from combustion.
Reduction of energy costs is moving along two parallel paths. One is to improve energy efficiency. In the US, fuel efficiency has been improved approximately 27% in 1994 compared to 1974, dropping from 7.5 MJ/kg to 5.5 MJ/kg. The other path is through change of fuel mix.

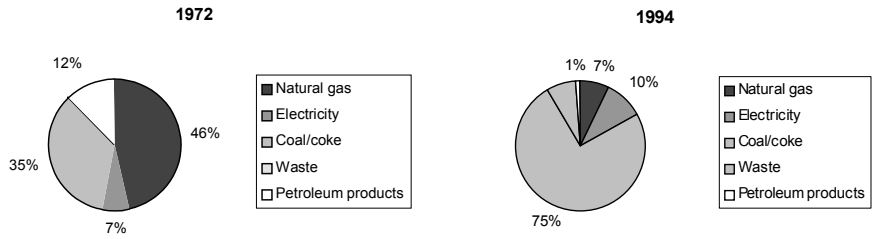


Figure 2.6 Average Energy Mix - US Cement Plants (%) [PCA Economic Research department US cement Industry Fact Sheet, Fourteenth Ed]

2.8 EMISSIONS FROM CEMENT MANUFACTURE

2.8.1 General view on emissions from cement production process

During the production of cement the main emissions occurring are dust and gaseous emissions. Table 2.10 and Table 2.11 give an overview of the emission rates from cement production. Table 6.1 (page 107) gives an overview of existing legislation on emission standards in some European Union Member States.

Dust emissions
To produce 1 kg of cement, between 1.5 and 2.0 kg of raw material must be pulverised. The machineries operate in large extent under (slightly) sub-atmospheric pressures. About 6 to 12 m^3 of air per kg of produced cement coming from the grinding process must be cleaned. The exit gases from cement kilns are dedusted in filters, normally electrostatic precipitators. The recovered dust (5-10% of the raw material) is sometimes recycled to the main process, either being added to the raw material preparation system, being insufflated into the sintering zone alongside the fuel injection or fed into the cement mills. In other cases collected dust is disposed of. The remaining dust emissions amount to about 25-100 mg/Nm^3 dry. Average dust emissions amounts to about 0.2 g/kg cement produced. The exhaust gases cleaned from dust are sent to the main stack.

Gaseous emissions
The gaseous emissions consist mainly of nitrogen from the combustion air, carbon dioxide from the calcination and combustion process, water from raw material and combustion process, and excess oxygen. The exit gases also contain chlorides, fluorides, sulphur compounds, nitrogen oxides, carbon monoxide, carbon dioxide and small amounts of dioxin and furan compounds. In addition traces of numerous heavy metals may be emitted. For the most important emitted substances a short description is given. The emissions of carbon dioxide are more extensively described.

Chlorides: The content of chlorides in the raw materials ranges between 0.01 and 0.1 mass-%. The chlorides react in the kiln to form alkali chlorides, which are bonded to dust particles. Except some hydro chloric acid practically no chlorides are present in the flue gases and released to the air.
Fluorides. The content of fluorides in the commonly used raw material ranges between 0.03 and 0.08 mass-%. HF is very volatile, and is captured by alkalis. Gaseous fluorides are not emitted to the air.
Sulphur. The content of sulphur in the raw material can be as high as 0.6% S, mainly in the form of pyrite and marcasite. The sulphur content of the fuel differs widely from fuel to fuel.
The sulphur from the fuel forms SO_2 in the burning zone of the kiln, which subsequently reacts with oxygen and alkalis to form alkali sulphates. The alkali sulphates may end up in the clinker or in kiln dust. Significant amounts of SO_2 are emitted when the raw materials contain sulphide compounds. The amount of SO_2 emitted depends on the choice of fuel and raw material. On average 0.12 g/kg cement is emitted, and concentrations between 200 and 400 mg/Nm^3 (10% oxygen) can be attained by using raw material with low sulphur content. A further reduction can be obtained by end-of-pipe equipment. This is, however, seldomly applied.
Nitrogen oxides. Practically all NO_x emissions are thermal NO_x emissions. Fuel related NO_x emissions are relatively small. High NO_x emissions are due to the high flame temperature (2000 °C) and material temperatures (up to 1500 °C). The NO_x emissions (as NO_2) amount to about 500 to 2000 mg/Nm^3 dry flue gas (11% oxygen). NO_x can be reduced by end-of-pipe measures as Selective Non-Catalytic Reduction (SNCR) which is applicable to preheater kilns.

Dioxin and furan compounds. The high temperatures in the kiln prevent formation or destroy the organic compounds. However, in a later stage these compounds can still be formed. Measurements showed that the concentration of TCDD in cleaned flue gases are generally much lower than the emission standard of 0.1 ng/Nm^3 dry flue gas.

Carbon dioxide

Carbon dioxide emissions in cement manufacturing come directly from combustion of fossil fuels and from calcining the limestone in the raw mix. An indirect and significantly smaller source of CO_2 is from consumption of electricity assuming that the electricity is generated from fossil fuels. Roughly half of the emitted CO_2 originates from the fuel and half originates from the conversion of the raw material. The total CO_2 emission for 1 kg cement is given in Figure 2.9. Not accounted for are the carbon dioxide emissions attributable to mobile equipment used for winning of raw material, and used for transport of raw material and cement, and used on the plant site.

Carbon dioxide emission from calcination

Process CO_2 is formed by calcining which can be expressed by the following equation:

$$\underset{1\ kg}{CaCO_3} \rightarrow \underset{0.56\ kg}{CaO} + \underset{0.44\ kg}{CO_2}$$

The share of CaO in clinker amounts to 64-67%. The remaining part consists of silicon oxides, iron oxides and aluminium oxides. CO_2 emissions from clinker production amounts therefore to about 0.5 kg/kg. The specific process CO_2 emission per tonne of cement depends on the ratio clinker/cement. This ratio varies normally from 0.5 to 0.95.

Carbon dioxide emissions from fuel use

Practically all fuel is used during pyroprocessing: fuel is burned in the rotary kiln and raw meal flows counter-current to a stream of hot gas. The pyroprocess removes water from the raw meal, calcines the limestone at temperatures between 700 and 900 °C and finally clinker the kiln material at about 1500 °C. The amount of carbon dioxide emitted during this process is influenced by the type of fuel used (coal, fuel oil, natural gas, petroleum coke, alternative fuels (see section 3.2)). Emission factors (EF_{CO2}) of fuels can be found in Annex 4 (page 109). The direct EF_{CO2} of waste fuels is considered to be zero. The argument is that the input of waste replaces an equivalent amount of fossil-fuel-derived energy, and the CO_2 would probably have been released (in the short or longer term) to the atmosphere without useful application of the energy content. In the case the use of waste is in competition with other uses, the replacement of fossil fuel and the avoidance of carbon dioxide emissions should be considered in more depth.[1] Indirect CO_2 is

[1] According to the waste definition of the EU (council directive 75/442/EEC and 91/156/EEC) *waste* means any substance or object which the holder discards or intends or is required to discard. According to a Waste forum of DGXI (June 1996), *waste* is not an indication of a specific property. It merely describes a *situation*, a transition in the life of a given product/material namely from being useful to a given purpose to being no longer needed by the owner, but it might still be useful for somebody else or for other purposes.

produced when alternative fuels are transported, processed and blended. In this study, we consider all carbon containing wastes replace fossil fuels in energy needed processes to be CO_2 neutral.

A typical mass balance for a dry-process cement production plant is given in Figure 2.8.

The total CO_2 emission during the cement production process depends mainly on:

- Type of production process (efficiency of the process and sub-processes)
- Fuel used (coal, fuel oil, natural gas, petroleum coke, alternative fuels)
- Clinker/cement ratio (percentage additives)

Figure 2.9 and Figure 2.10 depict the carbon dioxide emission from the cement production (dry-process) for various fuels in relation to the clinker/cement ratio. The cement/clinker ratio may vary by adding more or less additives to the cement. Table 2.1 (page 3) gives an overview of additives used in various types of cement.

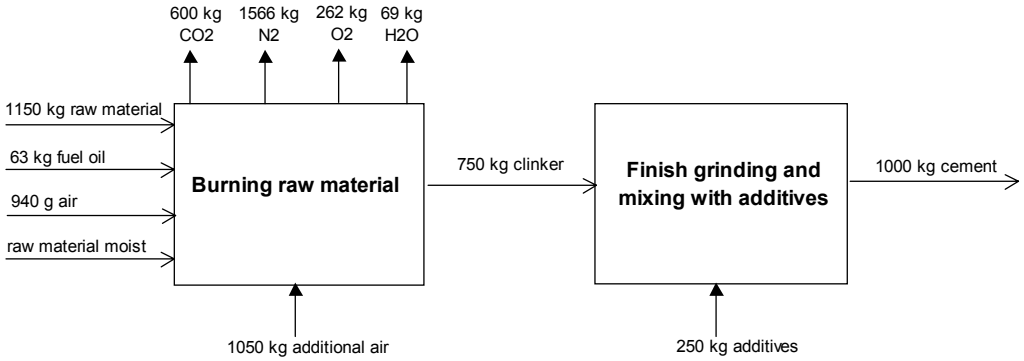


Figure 2.7. Mass balance for the production of 1 tonne of cement. (Raw material/clinker ratio: 1.54; clinker/cement ratio: 0.75; fuel use 3.35 MJ fuel oil/kg clinker; energy content fuel oil: 40 MJ/kg; 10% excess air).

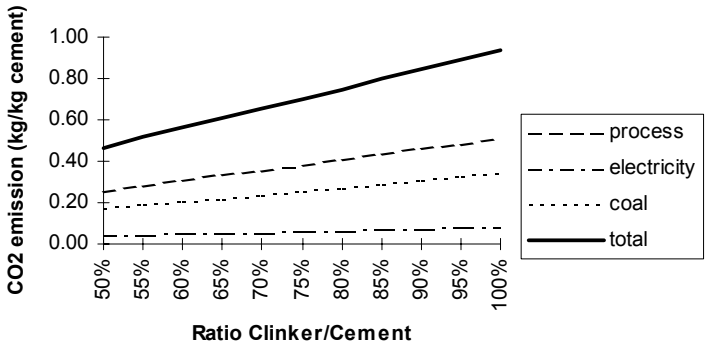


Figure 2.8. Total CO_2 emissions (energy and raw material related) from cement production process using coal, as a function of the clinker/cement ratio. (Fuel use: 3.35 MJ/kg of clinker; electricity use: 0.38 MJe/kg of clinker; Average emission factor of CO_2 of electricity production: 0.22 kg/MJe.)

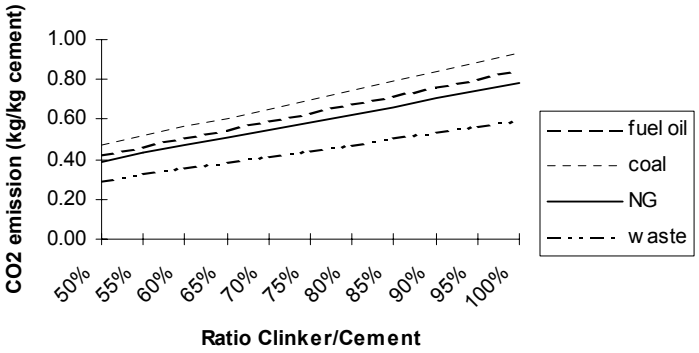


Figure 2.9 Total CO_2 emissions (energy and raw material related) from cement production process using various fuels, as a function of the clinker/cement ratio. See for assumptions caption of Figure 2.9. Assumed is no nett CO_2 emission from waste.

Table 2.10. Overview of the emission rates (mg/Nm^3, half hourly values, 10 vol-% O_2)

	Average	Minimal emission concentration	Maximal emission concentration
Dust	20	1	50
Nitrogen oxide (as NO_2)	750	300	1200
Sulphur dioxide (SO_2)	100	10	750
Carbon monoxide (CO)	1500	60	4000
As, Co, Ni, Pb (together)	$3\ 10^{-2}$	$0.2\ 10^{-2}$	$10\ 10^{-2}$
Cadmium (Cd)	$5\ 10^{-3}$	$0.1\ 10^{-3}$	$30\ 10^{-3}$
Thallium (Tl)	$5\ 10^{-3}$	$0.2\ 10^{-3}$	$20\ 10^{-3}$
Beryllium (Be)	$5\ 10^{-4}$	$0.3\ 10^{-4}$	$15\ 10^{-4}$
Mercury	$7\ 10^{-3}$	$0.1\ 10^{-3}$	$20\ 10^{-3}$
Organic carbon (TOC)	30	1	1000

Table 2.11. Overview of the specific emissions (g/t cement)

	Average	Minimal emission concentration	Maximal emission concentration
Dust	170	50	250
Nitrogen oxide (as NO_2)	1600	700	2700
Sulphur dioxide (SO_2)	12	15	430
Carbon monoxide (CO)	900	270	2100
As, Co, Ni, Pb (together)	$10\ 10^{-3}$	$2\ 10^{-3}$	$50\ 10^{-3}$
Cadmium (Cd)	$2\ 10^{-3}$	$3\ 10^{-3}$	$8\ 10^{-3}$
Thallium (Tl)	$7\ 10^{-3}$	$0.3\ 10^{-3}$	$40\ 10^{-3}$
Beryllium (Be)	$2\ 10^{-4}$	$4\ 10^{-6}$	$20\ 10^{-4}$
Mercury	$15\ 10^{-3}$	$20\ 10^{-6}$	$30\ 10^{-3}$
Organic carbon (TOC)	25	10	50

Table 2.12. Composition of waste gas into dust collector and operating conditions of cement kilns (typical ranges) [Cembureau, 1997]

		Dry process		**Semi-dry/semi-wet**	**Wet process**
		Compound operation (raw mill on)	**Direct operation (raw mill off)**		
Specific volume flue gas	(Nm^3/kg clinker)	2.1-2.5	1.7-2.0	1.8 – 2.2	3.2 – 4.2
Waste gas analyses	CO_2 (%)	22 –14	33 - 20	29 - 20	25 – 18
	O_2 (%)	8 –13	5 –9	4 - 10	4 – 8
	CO (%)	< 0.1	< 0.1	< 0.1	< 0.1
Temperature	°C	90 –150	120 - 200	90 - 150	130 - 180
Dewpoint	°C	45 – 60	50 - 65	50 -65	65 -75
Dust load (dry, standard conditions)	g/m^3				

2.8.2 Carbon dioxide emissions from cement production for various regions in the world

2.8.2.1 Methodology of Emissions Estimates

In this section we provide an estimate of both process and energy emissions from global cement production in 1994. This estimate is based on current, publicly available data for the cement sector. Carbon emissions were calculated in several steps. First, the top 27 producing countries accounting for 83% of cement production in 1994 were identified according to ten (10) regional groupings (Africa, Latin America, North America, Eastern Europe and the former Soviet Union (EE/FSU), Europe, India, China, OECD Pacific, Other Asia, Middle East). These key countries formed the basis of our global estimate. The remaining 132 countries were grouped within the rest of each region (e.g. ”Rest of Africa”).

2.8.2.2 Carbon Dioxide Emissions from Calcination

Following this grouping estimates were made of the amount of clinker produced in the key countries in order to calculate process carbon dioxide emissions associated with clinker production. For the process emissions a calcination factor of 0.136 MtC/t clinker (0.5 $MtCO_2$/t clinker)[1] was applied to each metric ton of clinker produced [Worrell, 1995]. Actual clinker production data was collected for Brazil, Mexico, the United States, Canada, Germany, India, China, Japan and Korea [PCA, 1996; Bundesverband der Deutschen Zementindustrie e.V., 1997; Government of India, 1996; Sinton, 1996; Korean Cement Industry Association, 1997]. For other key countries, clinker production was estimated by referring to data from previous years or assuming that clinker capacity utilisation for 1994 was the same as cement utilisation capacity as calculated from Cembureau statistics [Worrell, 1995; Cembureau, 1996]. For those non-key countries for which no specific clinker production data was available, we used an estimated average for the clinker/cement ratio. We divided the countries into either industrialised countries and rest-of-world and into two groupings—84% for industrialised countries and 87% for rest-of-world—based on a weighted average of actual clinker to cement ratio data collected for key countries.

2.8.2.3 Carbon Dioxide Emissions from Fuel Use

To calculate energy-related carbon dioxide emissions from fossil fuel consumption, we first collected 1994 data on the average specific fuel consumption per tonne clinker (GJ/t) for key countries, or for the closest year to 1994 for which there was available data. Actual intensity data for industrialised countries were collected for Canada, Germany, France, Italy, Japan, Korea, Spain, Turkey, and the United States [CIEEDAC, 1996; Bundesverband der Deutschen Zementindustrie e.V., 1997; Cembureau, 1997; Cowiconsult, 1993, Korean Cement Industry Association, 1997; Energy Information Administration, 1997; PCA, 1996; Cembureau,

[1] 1 Mt CO_2 = 0.27 Million tonne Carbon (MtC) = 0.27 TgC

1996]. Fuel intensity data for developing and EE/FSU countries collected included, Argentina, Brazil, China, Columbia, Egypt, India, Mexico, Poland, and Venezuela, [Van der Vleuten, 1994; Ministry of Mines and Energy, 1997; Sinton, 1996, Central Statistical Organisation, 1995; Secretaria de Energia, 1997; Cembureau, 1997].[1] For other key countries (Morocco, South Africa, Ukraine Russia, Thailand, Taiwan, Indonesia, Saudi Arabia, and Iran) we used Cembureau statistics and calculated the share of wet and dry kiln technology per country. We then applied an intensity factor of 5.9 GJ/t clinker for wet kilns and 3.5 GJ/t clinker for dry kilns to calculate weighted fuel intensity for these key countries. For countries where fuel intensity data was not available we grouped into two groupings, industrialised countries and rest-of-the-world and applied an average weighted fuel intensity (based on actual key country data collected) of 3.5 GJ/t clinker for industrialised countries and 4.2 GJ/t clinker for rest-of-world countries. We then used national statistics and Cembureau data to calculate weighted carbon emissions factor of fossil fuel inputs for cement production by country.[2]. The carbon emissions factors for fuels ranged roughly from 16 ktC/PJ to 29 ktC/PJ depending on the actual fuel mix for the kilns in any particular country. A weighted fuel carbon emissions factor was calculated for the each rest-of-region grouping.[3]

2.8.2.4 Carbon Dioxide Emissions from Electricity Use

Our final step of carbon emissions calculations was to calculate emissions from electricity consumption. Specific electricity consumption data was collected for the same key industrialised and developing countries as was collected for fuel consumption data (Canada, Germany, France, Italy, Japan, Korea, Spain, Turkey, United States, Argentina, Brazil, China, Columbia, Egypt, India, Mexico, Poland, and Venezuela). For all other countries and regional groupings electricity intensity for all kilns was estimated at 0.3 GJ/t cement for industrialised countries, and 0.4 GJ/t cement for the rest-of-the-world. We then used International Energy Agency statistics to calculate the average carbon intensity of fuel inputs for public electricity generation for each country and regional grouping [IEA, 1997][4].

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[1] Fuel intensity estimates for industrialized countries in GJ/t and the estimate year are: Canada 3.8 (1994), Germany 3.3 (1995), France 3.8 (1995), Italy 4.1 (1995), Japan 2.4 (1993), Korea 3.2 (1994), Spain 3.5 (1995), Turkey 3.9 (1995), United States 4.5 (1994). Intensity estimates for rest of world countries are: Argentina 4.3 (1990), Brazil 3.7 (1994), China 4.8 (1994), Colombia 5.9 (1990), Egypt 4.8 (1990), India 4.2 (1994), Mexico 3.5 (1994), Poland 5.3 (1995), Venezuela 5.0 (1990). Mexico is grouped with other Latin American countries in our analysis although it is an OECD member country.

[2] We used Intergovernmental Panel on Climate Change (IPCC) recommended carbon emissions factors for fuel inputs. Factors in ktC/PJ were as follows: petroleum coke – 30.0, coal – 25.8, fuel oil – 21.1, natural gas – 15.3, and biomass – 29.9.

[3] Actual fuel emissions factors in ktC/PJ by country were as follows: Turkey 29.13, Spain 28.98, Morroco 27.69, Taiwan 25.84, Germany 25.83, South Africa 25.80, Poland 25.78, Japan 25.68, Rest of Europe 25.62, China 25.61, India 25.59, Korea 25.42, Thailand 25.35, United States 25.15, Italy 24.91, France 24.31, Colombia 24.01, Rest of Other Asia 23.95, Canada 23.94, Brazil 23.58, Rest of Latin America 23.19, Indonesia 21.85, Rest of OECD Pacific 21.71, Egypt 20.69, Mexico 20.44, Rest of Middle East 20.32, Rest of Africa 20.16, Rest of EE/FSU 19.01, Iran 18.95, Saudi Arabia 18.89, Russia 18.02, Venezuela 17.58, Argentina 16.38, and Ukraine 15.62

[4] Actual electricity carbon intensities in ktC/PJ for the various countries and regional groupings for 1994 were as follows: Ukraine 90.30, India 90.30, China 73.63, South Africa 73.53, Poland 72.97, Morroco 71.38, Iran 58.89, Indonesia 56.92, Saudi Arabia 56.91, Turkey 56.80, Thailand 56.20, Egypt 54.64, Rest of OECD Pacific 51.29, Rest of Middle East 50.58, USA 47.30, Taiwan 42.87, Mexico 40.76, Russia 40.04, Italy 39.25, Germany 37.67, Rest of EE/FSU 37.22, Rest of Africa 36.82, Spain 35.92, Rest of Other Asia 35.69, Argentina 33.03, Japan 32.72, Korea 29.32, Colombia 20.87, Venezuela 20.26, Rest of Latin America 15.57, Rest of Europe 14.89, Canada 14.64, France 4.88, Brazil 3.42. For the Netherlands, we included statistics on public CHP generation given the high share of public CHP in that country.

2.8.2.5 Carbon Emissions from Cement Production

Carbon emissions from cement production are due to both the calcination of limestone to clinker (process emissions) and the combustion of fossil fuels. Estimated carbon emissions from cement production in 1994 were 307 Million Metric tonnes of Carbon (MtC), 160 MtC from process carbon emissions and 147 MtC from energy use. These emissions account for 5.0% of 1994 world carbon emissions based on a total of 6199 MtC reported by the Carbon Dioxide Information and Analysis Center [Marland, 1998].

below provides carbon dioxide emissions estimates (in million metric tonnes of carbon) by key producing countries and regions. Of the countries shown, China accounts for by far the largest share of total emissions (33.0%) followed by the United States (6.2%), India (5.1%), Japan (5.1%), and Korea (3.7%). Overall, the top ten cement producing countries in 1994 accounted for 63% of global carbon emissions from cement production for that year. Regionally, after China, the largest emitting regions are Europe (11.5%), OECD-Pacific (9.3%), Other Asian Countries excluding China and India (9.3%), and the Middle East (8.4%). World average primary energy intensity was 4.8 GJ/t, with the most energy intensive regions being Eastern Europe and the former Soviet Union (5.5 GJ/t), North America (5.4 GJ/t) and the Middle East (5.1 GJ/t).

The average world carbon intensity of carbon emissions in cement production is 222 kgC/tonne cement. While China is the largest emitter, the most carbon intensive cement region in terms of carbon emissions per tonne of cement produced is India (253 kgC/tonne), followed by North America (242 kgC/tonne), and then China (240 kgC/tonne). Figure 3.1 below shows the carbon intensity of cement production in various regions.

Table 2.13 1994 Global Carbon Emissions from Cement Production

	Cement Production	Clinker/ Cement Ratio	Primary Intensity	Primary Energy	Process Carbon Emissions	Carbon Emissions. Energy Use	Total Carbon Emissions	Share of World Total
	Mt	%	GJ/t	PJ	MtC	MtC	MtC	MtC
CHINA	423	83%	5.0	2117	47.7	53.7	101.4	33.0%
EUROPE	181.9		4.1	749	20.0	15.3	35.3	11.5%
Italy	33.2	80%	4.5	150	3.6	3.2	6.8	2.2%
France	21.2	74%	4.1	88	2.1	1.5	3.6	1.2%
Germany	36.1	79%	3.8	137	3.9	2.8	6.7	2.2%
Spain	26.7	81%	3.9	104	2.9	2.5	5.5	1.8%
Rest of Europe	64.7	84%	4.2	271	7.4	5.2	12.5	4.1%
OECD PACIFIC	151.3		3.5	533	17.6	11.0	28.6	9.3%
Japan	91.6	80%	3.1	280	9.9	5.7	15.6	5.1%
Korea	51.6	96%	4.3	220	6.7	4.6	11.4	3.7%
Rest of OECD Pacific	8.0	84%	4.2	34	0.9	0.7	1.6	0.5%
Other ASIA	123.8		4.9	613	15.3	13.3	28.6	9.3%
Thailand	31.1	90%	4.8	148	3.8	3.4	7.2	2.4%
Taiwan	23.2	95%	4.9	114	3.0	2.5	5.5	1.8%
Indonesia	21.9	96%	5.3	115	2.9	2.4	5.3	1.7%
Rest of Other Asia	47.6	87%	4.9	235	5.6	4.9	10.5	3.4%
MIDDLE EAST	111.2		5.1	563	13.8	12.0	25.8	8.4%
Saudi Arabia	16.0	87%	4.7	75	1.9	1.4	3.3	1.1%
Egypt	16.1	99%	5.8	93	2.2	1.9	4.1	1.3%
Iran	15.9	97%	5.3	84	2.1	1.6	3.7	1.2%
Turkey	31.9	90%	4.9	156	3.9	4.1	8.0	2.6%
Rest of Middle East	31.4	87%	4.9	155	3.7	3.0	6.7	2.2%
NORTH AMERICA	88.4		5.4	480	10.6	10.8	21.4	7.0%
USA	77.9	88%	5.5	427	9.3	9.6	18.9	6.2%
Canada	10.5	88%	5.1	53	1.3	1.2	2.5	0.8%
EE/FSU	100.7		5.5	558	11.4	10.3	21.7	7.1%
Poland	14.9	82%	5.6	83	1.7	2.1	3.8	1.2%
Ukraine	11.4	80%	6.0	68	1.3	1.3	2.6	0.8%
Russia	37.2	80%	6.0	223	4.1	3.8	7.8	2.5%
Rest of EE/FSU	37.1	87%	4.9	183	4.4	3.2	7.6	2.5%
LATIN AMERICA	97.4		4.7	462	11.2	8.2	19.4	6.3%
Brazil	25.2	77%	4.1	102	2.6	1.7	4.4	1.4%
Mexico	29.8	88%	4.5	133	3.6	2.5	6.0	2.0%
Colombia	8.3	82%	6.1	51	0.9	1.0	2.0	0.6%
Venezuela	7.5	87%	5.7	43	0.9	0.6	1.5	0.5%
Argentina	6.3	90%	5.3	33	0.8	0.5	1.3	0.4%
Rest of Latin America	20.2	87%	4.9	100	2.4	1.9	4.2	1.4%
INDIA	62.4	89%	5.0	309	7.6	8.2	15.8	5.1%
AFRICA	41.0		4.9	201	4.9	4.2	9.0	2.9%
Morocco	6.3	85%	4.8	30	0.7	0.8	1.5	0.5%
South Africa	7.9	90%	4.9	39	1.0	1.0	1.9	0.6%
Rest of Africa	26.8	87%	4.9	132	3.2	2.4	5.6	1.8%
WORLD TOTAL	1380.9	85%	4.8	6585	160	147	307	100.0%

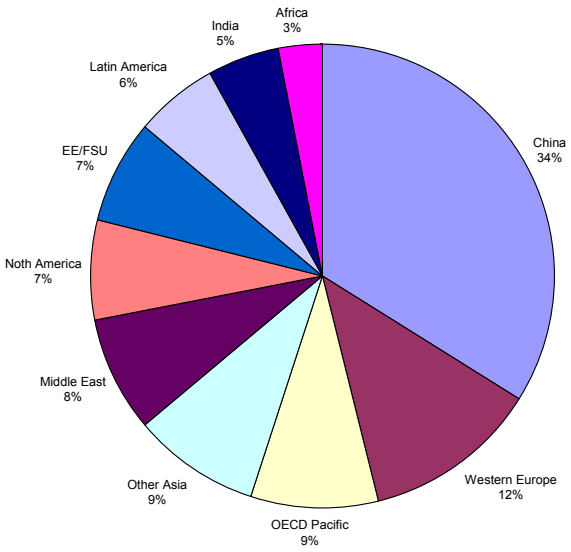

Figure 2.10 Share of Carbon Emissions from Cement Production by World Region, 1994

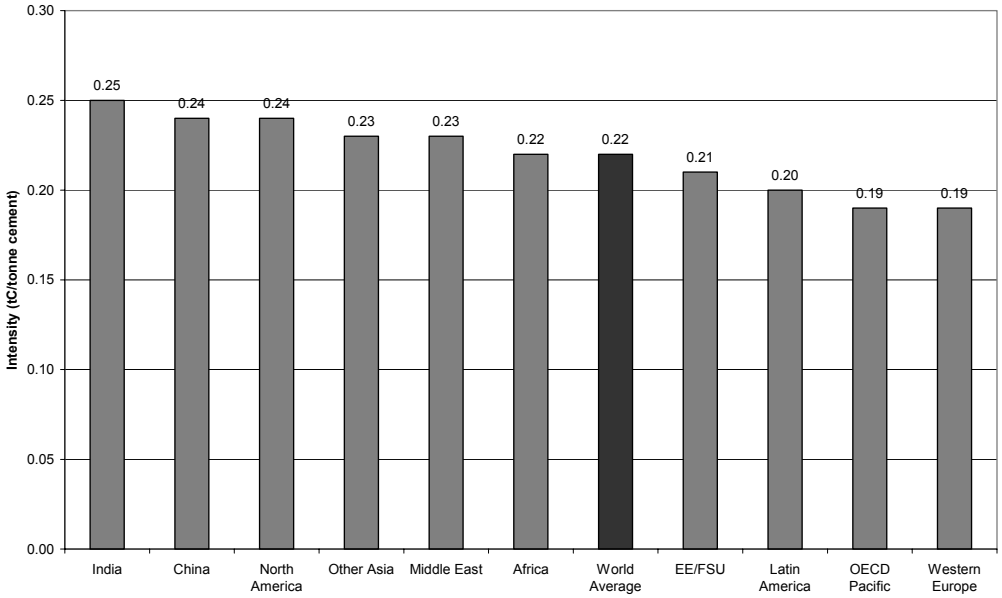

Figure 2.11 Carbon Intensity of Cement Production (tC/tonne)

3. REDUCTION OF CARBON DIOXIDE EMISSIONS

Emissions of carbon dioxide can be reduced by:

- improvement of the energy efficiency of the process
- shifting to a more energy efficient process (e.g. from wet to dry process)
- replacing high carbon fossil fuels by low carbon fossil fuels
- replacing fossil fuels by alternative fuels, e.g. waste-derived fuels
- applying lower clinker/cement ratio (increasing the ratio additives/cement): blended cements.
- application of alternative cements (mineral polymers)
- removal of CO_2 from the flue gases

These options will be discussed in this chapter.

3.1 ENERGY EFFICIENCY IMPROVEMENT AND SHIFTING TO MORE ENERGY EFFICIENT PROCESSES

The production of cement is an energy-intensive process that results in the emissions of carbon dioxide from both the consumption of fuels (primarily for the kiln) and from the calcination of limestone. Clinker production is the most energy intensive production step, responsible for about 70-90% of the total energy consumed. Raw material preparation and finish grinding are electricity intensive production steps.

Improvement of energy efficiency reduces the emissions of carbon dioxide and may reduce the costs of producing cement. Improvement may be attained by applying more energy efficient process equipment and by replacing old plants or kilns by new ones. Table 3.1 summarises the main practices and measures for energy efficiency improvement in cement making. We will briefly describe the main measures and discuss the applicability. The measures are described in more detail in Annex 1.

3.1.1 Energy Efficiency Improvement Measures

General. Plant wide there are various measures that can be applied to improve energy efficiency op cement and clinker making. The most important ones are process control systems for the kiln and for the grinding mills. Various process control systems have been developed for kiln, and have been implemented successfully in cement plants around the world. Ranging from the LINKman system that was developed in the United Kingdom, and used in many cement plants, to new systems using neural networks or 'fuzzy logic'. Neural networks are a second-generation process control system that tries to simulate the best operator, using data collected from the process operations. The savings on clinker fuel use vary between 2 and 10%, and power savings are estimated at 3-4 kWh/tonne clinker [ETSU, 1988; Haspel and Henderson, 1993]. The payback period of such systems is very short, also due to increased productivity. These systems also lead to reduced NOx emissions. Other general measures are found in the drive systems of motors, by install-

ing high efficiency motors or adjustable speed drives. High efficiency motors may induce power savings varying from 3% to 8% [Fuijmoto, 1993; Vleuten, 1994], while adjustable speed drives may lead to savings depending on the motor application, varying between 0% and 70% [Bösche, 1993]. We estimate the savings at typically 10 kWh/tonne cement. The investments for new motor systems can be high and are often only cost-effective when there is a need to replace an existing motor system.

Raw Meal Preparation. Grinding is the largest electricity consumer in cement making. Grinding of the raw materials may consume between 12 and 22 kWh/tonne raw material, or often even higher due to inefficient use of equipment. Roller presses or roller mills can reduce the power consumption considerably, when compared to the ball mill. Ball mills are still the dominant grinding process throughout the world. Installing a new roller press may substantially increase the grinding capacity, while reducing power use by up to 40-50%. However, installing a new grinding mill is often only cost-effective in regions with high electricity costs, or when replacing older equipment. Improved homogenising systems and transport systems for the raw meal may also contribute to increased power savings. The power savings are estimated at 1.4 – 4.0 kWh/tonne clinker [Fujimoto, 1993; Holderbank, 1993; Alsop and Post, 1995]. The payback period of these systems are very high, if there are besides the power savings no additional savings are obtained. Hence, new homogenising systems are only considered in new plants, or when retrofitting an existing site.

Clinker Kiln. The kiln is the largest fuel consumer, and the dominant source of carbon dioxide emissions from cement making. The emissions depend on the kiln type, fuel used and efficiency of the kiln (see Chapter 2). Large energy savings can be achieved by changing from a wet process kiln to the modern pre-calciner dry process kiln. Such a conversion would not only cut fuel use in almost half, but also increase the production capacity substantially. Power use is typically somewhat higher. Process conversion is an important option in areas with high fuel prices, strict environmental control, or when expanding the production capacity of an existing plant. The investment costs are estimated at approximately 130 $/tonne capacity, which is very expensive from the point of energy savings alone. However, increased production capacity, lower operation costs make this measure more cost-effective. Other kiln conversions (to semi-wet or semi-dry) are also implemented to convert existing wet kilns to more energy efficient kilns.
Older long dry kilns may be converted to pre-heater or pre-calciner kilns by adding pre-heaters or a pre-calciner kiln. In a pre-calciner the raw materials are pre-calcined up to 90%, before entering the kiln, using waste heat from the kiln. This not only reduces energy intensity by 11-14% (Sauli,1993) compared to a pre-heater kiln, but also increase the capacity by 80-100%. Modern rotary kilns are always of the multi-stage pre-heater or pre-calciner type, when the humidity of the raw materials allows it. Costs of converting an existing dry kiln to a multi-stage preheater or pre-calciner kiln are estimated at 30-40 US$/tonne capacity.

In Lepol or semi-dry kilns the raw meal preheating can be improved, reducing fuel use by approximately 0.2 GJ/tonne clinker, while increasing process output [Crossila and Häutle,1997]. No investment costs were given for this measures.

The clinker is cooled when leaving the kiln. Various clinker coolers exist, of which the grate cooler is the modern variant. Replacing an older cooler by a new grate cooler may increase energy recovery by 0.1 – 0.3 GJ/tonne clinker [Vleuten,1993]. Cooler conversion is only attractive when installing a pre-calciner to use the recovered waste heat.

Other measures in rotary kilns are replacement of the burner to allow better mixing of the fuel and air and improve heat transfer in the kiln, reduction of heat losses through the kiln shell through improved insulation. It is also possible to generate steam from the waste heat to generate power. This is only attractive in areas where power outages are common, or electricity is very expensive. Savings of these measures are limited to a few percent of typical kiln energy use. Installing new burners is economically attractive with a short payback period, while the other two measures are generally economically not attractive, except under special circumstances.

Shaft kilns are mainly used in China and India, as well as for the production of speciality cements. In China energy efficiency packages have been developed for shaft kilns that may reduce energy consumption by 10 to 30%, with a payback period of less than two years [Feng, 1995].

Finish Grinding. Grinding of cement clinker, together with additives to control the properties of the cement (e.g. fly ash, blast furnace slag, pozzolona, gypsum and anhydrite) can be done in ball mills, roller mills, or roller presses. Combinations of these milling techniques are often applied. Coarse material is separated in a classifier to be returned for additional grinding. Power consumption for grinding depends strongly on the fineness required for the final product and the additives used (in intergrinding). Electricity use for raw meal and finish grinding depends strongly on the hardness of the material (limestone, clinker) and the desired fineness of the cement as well as the amount of additives. Blast furnace slags are harder to grind and hence use more grinding power. Traditionally, ball or tube mills are used in finish grinding, while many plants use vertical roller mills. Modern state-of-the-art concepts are the high-pressure roller mill and the horizontal roller mill [Seebach *et al*., 1996]. Ball mills may use between 32 and 37 kWh/tonne [Seebach *et al*., 1996] for cements with a Blaine of 2950-3200 cm2/g. Replacing ball mills by efficient high pressure roller presses may reduce power consumption to 23-28 kWh/tonne cement, or a saving of up to 40% [Buzzi, 1997]. Investment costs may vary widely. Generally, the installation of a roller press is economically attractive when expanding capacity, replacing an older mill, or constructing a new plant.

The use of high efficiency classifiers may reduce power consumption by approximately 2.0 kWh/tonne cement [Salzborn and Chin-Fatt, 1993], with investment costs of 2.5-3 US$/tonne cement [Holderbank,1993]. There is still substantial potential for the application of high efficiency classifiers. In the European Union approximately a third of the classifiers were estimated to be high efficiency classifiers [Cowiconsult, 1992].

Table 3.1. Energy efficiency improvement options for cement production processes

Technique	Description	Emission reduction/ energy improvement	Economics
Process Control and Management Systems	Automated computer control may help to optimise the combustion process and conditions	Typically 2.5-5%	Economics of advanced processes very good (pay back time as short as 3 months)
Raw Meal Homogenising Systems	Use of gravity-type homogenising silos	Reduction power use (1.4-4 kWh/t clinker)	No information available for this study
Conversion from Wet to Semi-Wet Process	Moisture content of raw meal reduced by slurry press filter.	0.8-1.6 GJ/t clinker (3-5 kWh increase of power consumption)	Reduced fuel costs partially offset the costs.
Conversion from Wet to Dry Process	Complex operation, leaving only the structural parts intact	Estimated at 2.2 GJ/t (increase of power by about 10 kWh/t)	High costs (133 US$/t annual capacity), but vary across the world. May be economically feasible
Conversion from dry to multi-stage preheater kiln	Four or five stage preheating reduces heat losses, and sometimes reduces pressure drop	Depending on original process. In one example reduction from 3.9 to 3.4 GJ/t	Estimated at 30-40 US$/t annual capacity
Conversion from dry to precalciner kiln	Increase of capacity, and lowering specific fuel consumption	Depending on original process. Estimated at 12% (0.44 GJ/t)	Estimated at 28 US$/t annual capacity
Conversion from Cooler to Grate Cooler	Large capacity and efficient heat recovery.	Reduction of 0.1-0.3 GJ/t (increase in power by 3 kWh/t)	Probably only attractive when installing a precalciner simultaneously
Improved Preheating (LEPOL Kiln)	Raw meal preheated in a two-stage grate preheater.	Fuel saving of 6.3% (to 3.3 GJ/t). 1% less power use	Payback time reported to be satisfactory
Optimisation of Heat Recovery in Clinker Cooler	Heat recovery improved by reduction of excess air volume, control of clinker bed depth and new grates.	Estimated at 0.5 GJ/t in the US, and 0.2 GJ/t in India	No specific cost information available for this study
High efficiency Motors and Drives	Variable speed drives, improved control strategies and high-efficiency motors	Estimated power savings ranging from 3 to 8%.	High-efficiency motors cost about the same or only little bit more than regular motors
Adjustable Speed Drives	Reducing throttling and coupling losses by replacing fixed speed AC motors	Estimated at 10 kWh/t cement	Depends strongly on size of system. Estimated at about 1 US$/t cement
Efficient Grinding Technologies	High-pressure mills (like the Horomill) has improved grinding characteristics	Estimated at 16-19 kWh/t (40-50%)	Estimates ranging from 2.5 to 8 US$/t annual capacity. Operation costs may be reduced by 30-40%
High-efficiency Classifiers	sharper separation, thus reducing overgrinding	Estimated at 1.7-2.3 kWh/t cement (8%)	Costs are estimated at 2.5-3 US$/t cement
Shaft Kilns: Efficient Kiln Technology (China)	Improved input control, kiln size and shape, insulation and computer control.	Estimated at 1.2 GJ/t for the 1990 mix (10-30%)	Investment estimated at 230 Yuan/t annual capacity. Pay back time of less than 2 years.
Fluidised bed Kiln	Rotary kiln replaced by stationary kiln leading to lower capital costs, wider variety of fuel use and lower energy use	Fuel use of 2.9 to 3.35 GJ/t clinker (also lower NO_x emissions)	Lower investment and maintenance costs expected
Advanced Comminution Technologies	Non-mechanical 'milling' technologies as ultrasound. Not commercially available in coming decades	Expected (theoretical) savings are large	No information available due to preliminary stage of development
Mineral Polymers	Mineral polymers are made from alumino-silicates leaving calcium oxide as the binding agent.	Preliminary estimates suggests 5 to 10 times lower energy use and emissions	No specific cost information was available for this study.

Advanced Technologies. Various advanced technologies have been proposed or are subject of research and development programmes. These technologies include the fluidized bed kiln [Cohen,1995], with a theoretically lower fuel consumption, lower emissions and lower investment costs, and non-mechanical comminution technologies [Suzuki, 1993]. Annex 1 provides a more detailed description of the technologies, as well as status of development.

3.1.2 Implementation of Energy Efficiency Improvement Measures

The relative high capital costs, and often low energy costs, combined with the long life-time of cement making equipment, makes it not always economically attractive to convert an existing plant to a more energy efficient processes. Although current low coal prices (the main fuel in cement making) decrease interest in energy efficiency improvement, energy costs still represent approximately 20-30% of the production costs of cement making. Generally in industry the main barriers in adopting energy efficient technologies are the effects on product quality, expected reliability of the new technology, and budgetary limits. These barriers seem to be valid for OECD, and for some economies in transition. Generally, in industrialised countries with slowly growing cement production the major energy savings in the past have been obtained by replacement not for energy efficiency goals, but to obtain increase in productivity. Observed barriers in the cement industry are the long lifetime of the equipment, fear for decreased product quality and doubts about the technical feasibility of a measure [Worrell *et al*., 1995]. Empirical research on implementation barriers in developing countries is very limited, but the barriers found in economies in transition and OECD countries might apply for these countries as well, besides various organisational barriers.

Generally, new kilns are more efficient than older kilns and may be found all over the world, and especially in developing countries, but also in industrialized countries, e.g. the U.S. More efficient plants can also be found in regions with relatively higher energy prices, e.g. Western Europe and Japan. A study by Holderbank [1993] showed that the share of energy costs in the production costs of cement was equal for plants operating in the U.S. and Canada and those operating in Europe, despite the much higher energy costs in Europe. European cement plants used less energy to produce a tonne of cement than the North-American plants. The U.S. has the highest share of wet process kilns of all OECD countries, except for the U.K. In the U.K. the limestone has a high humidity, reducing the advantages of the dry process. The share of the wet process in the U.S. clinker production has been declining, through closing of older plants and start-up of new plants in regions with increasing cement demand (e.g. the Northwest of the U.S.). Replacing wet process kilns for energy efficiency alone is not cost-effective, and hence accelerated retirement of wet process is only possible when replacing older facilities or introduction of blended cements (see section 3.3).

Measures can be subdivided in different classes, depending on the specific costs and the likelihood of implementation. We define three classes: energy efficiency, process replacement, new plants (see Table 3.2). ‘Energy efficiency measures’ are economically attractive to add to existing plants. ‘Process replacement measures’ are only cost-effective when increasing capacity of existing facilities or retiring old plants. ‘New plants’ captures those measures that are state-of-the-art when constructing new greenfield plans.

Table 3.2. Classes of energy efficiency measures, subdivided by most likely way of implementing the measures.

Energy Efficiency Measures
Process Control and Energy Management Conversion of a Wet Process Kiln to Semi-Wet Process Improved Preheating in Semi-Dry Process Kiln Optimisation of Heat Recovery in Clinker Cooler New Burners in Wet and Dry Process Kilns High Efficiency Classifiers Replacing Raw Meal and Finish Grinding Mills Adjustable Speed Drives Upgrading of old Shaft Kilns (China, India)
Process Replacement or Capacity Increasing Measures
Increasing Pre-heater Stages Installing Pre-Calciner Conversion of Wet Process to Dry Process Cooler Replacement by Grate Cooler Replacing Raw Meal and Finish Grinding Mills Installing New Motors
New Plants
Raw Meal Homogenising and Transport System Multi-Stage Pre-heater Precalciner Kilns High Pressure Roller Presses

3.1.3 Potentials for Energy Efficiency Improvement

The potentials for energy efficiency improvement vary widely by country and region. The estimates for the energy intensity of cement production vary by region, as shown in Table 2.13. This illustrates the variation in potentials for energy efficiency improvement. The primary energy intensity in Table 2.13 is influenced by the energy intensity of the used processes as well as share of blended cements in the product mix (see section 3.3). An earlier study by Worrell *et al*. [1995] estimated the potential for efficiency improvement, by comparing the actual energy consumption with that of a ‘best practice’ plant using a pre-calciner kiln for the same product mix of Portland and blended cements. The savings on primary energy varied from 0% to 57% relative to 'best available technologies' [Worrell *et al*.,1995]. The high potential savings in various countries are mainly due to the high share the wet process still has in the clinker production (e.g. Poland, USA and former-USSR).

3.1.4 Conclusions

Various options for energy efficiency improvement are available in all stages of cement production. The technical potential for efficiency improvement may vary between 0% and 60% depending on the technology used and the efficiency of operating the technology. High potentials for energy efficiency improvement can be found in regions with a high share of wet process kilns, e.g. the economies in transition in Central and Eastern-Europe and also in the U.S. Implementation of energy efficiency measures is hindered by the high capital costs and long life-time of cement making equipment and the relative low energy costs. Relatively high energy savings can be achieved through replacement of existing processes, at the end of

the economic lifetime of the processes or when increasing the production capacity of an existing facility. Still, substantial savings can be achieved through implementation of process control systems, high efficiency classifiers and other retrofit-measures. Increased use of blended cements (see section 3.3) could have synergies, by allowing closing of older facilities using the wet process or long dry kilns.

3.2 REPLACING HIGH (FOSSIL) CARBON FUELS BY LOW (FOSSIL) CARBON FUELS

More than 90% of the energy used in the cement production is originating from fuels. The rest (5-10%) of the energy consumption is electricity. A main option to reduce carbon dioxide emissions is to reduce the carbon content of the fuel. A historical analysis showed for the United States that the opposite trend is occurring. In 1972 natural gas formed a little less than 50% of the fuel applied; coal about 35%. In 1994 the share of coal was increased to 75% and that of natural gas lowered to 7%. In this period, the carbon intensity of the fuel had been increased by almost 30%.

The (long-cycle-fossil) carbon intensity of the fuels can be diminished by application of fossil fuels with a low(er) carbon intensity, for instance a switch from coal to natural gas. Another important opportunity to reduce the (long-cycle) carbon emission is the application of waste-derived alternative fuels. In the next section the advantages and disadvantages of this option are discussed.

3.2.1 Alternative fuels

Instead of fossil fuels, alternative (waste-derived) fuels could be used in the kiln. This could at the same time diminish the disposal of waste material and reduces the use of fossil fuels. Disadvantage may be the adverse effects on the cement quality and increased emission of harmful gases. Some types of alternative fuels:

- Gaseous alternative fuels
  - Coke oven gases, refinery gases, pyrolysis gas, landfill gas
- Liquid alternative fuels
  - Halogen-free spent solvents, mineral oils, distillation residues, hydraulic oils, insulating oils
- Solid alternative fuels
  - Waste wood, dried sewage sludge, plastic, agricultural residues, tyres, petroleum coke, tar

Alternative fuels may contribute to the cement process as an alternative source of energy and as a source of raw material: recovery of energy and material.[1] The organic fraction of waste can be used as a source of fuel. The mineral part of a waste can be used as raw material. Organic free mineral wastes can be added in the raw

[1] Types of waste, politically excluded (as a general rule) from recovery in cement kilns are pesticides, carcinogenic, pathogenic and other highly toxic hydrocarbons, asbestos, and biologically highly active substances. Excluded are also general household type unsorted waste (garbage, refuse). Furthermore, radioactive waste is excluded from recovery.

meal preparation. Wastes, contaminated with organics, may be introduced through the solid fuel handling, directly to the burning and/or calcining zone.[1]
Waste needs to be processed before it can be utilised in the cement kiln. Processing is required to obtain a fuel with constant quality that can easily be fired in the kiln. Fuel qualities of concern include heat content, solid content and volatile matter, viscosity, moisture content, ash constituents, and the levels of various other constituents as sulphur, nitrogen, metals, biocides, and halogenated organics. Several systems or techniques are developed to utilise waste in the manufacture of cement. The processing system contains transport, storage, processing, and feed system.

The European cement industry used in 1990 between 0.75 and 1 Mtonne per year of alternative fuels, equivalent to 25-35 PJ. In 1993, 9% of the thermal energy consumption in the European cement industry originated from alternative fuels. In 1995 this amounted to about 10%, equivalent to about 70 PJ. The proportion of alternative fuel is gradually increasing worldwide and figures above 50% are already achieved in certain regions. In a 1996, 10 plants reported using wastes as a primary fuel and 45 plants reported using wastes as alternate fuel. Many plants in Europe use waste, although no reported exact figure could be obtained. Figure 3.1 shows for various European countries the 1995-fuel mix in cement kilns. In these countries 435 PJ of fuel was used, from which 38 PJ (9%) originated from alternative fuel [Cembureau, 1997].

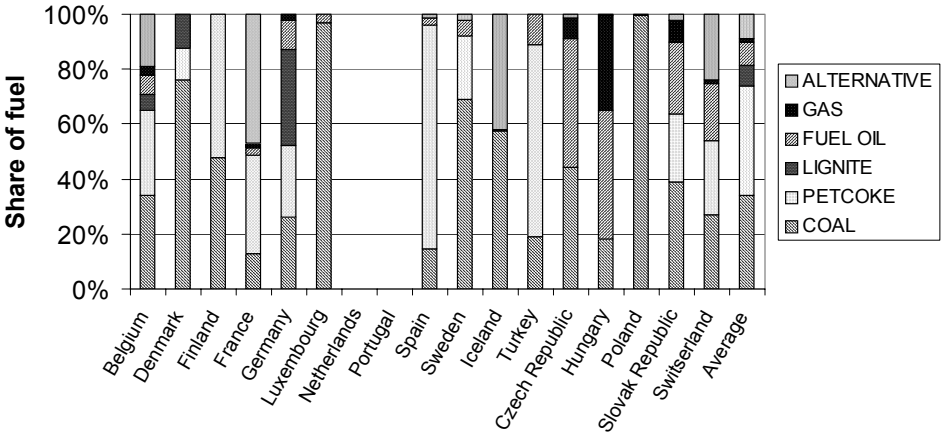

Figure 3.1. Share of various fuels in European countries.

[1] Some types of waste can be used in the cement production step, reducing the clinker/cement ratio (thus reducing CO_2 emissions, because less clinker is needed per kg cement). Examples of the additives are fly ash, blast furnace slag, and secondary gypsum. Some types of waste can be processed giving directly a cementitous product. Examples are paper and de-inking sludges can be transformed in activated clay; red mud from the aluminium industry can be transformed in a pouzzolanic material; some industrial slag can be re-melted and cooled in such a condition to be transformed in hydraulic or pozzolanic binder.

3.2.1.1 Carbon dioxide emission reduction potential of waste use in cement kilns

Input of waste replaces fossil fuels and consequently reduces carbon dioxide emissions from the cement manufacturing process. The amount of CO_2 avoided depends mainly on the amount and type of fuel replaced. Table 3.3 shows the CO_2 emissions for a typical dry and wet process for various fuels. The emission reduction is presented for three clinker/cement ratios (0.5; 0.75; 0.95) and two production efficiencies (3.35 and 5.4 MJ/kg clinker). In all cases the electricity production is based on fossil fuels.

Table 3.3 CO_2 emissions in kg per kg cement produced for dry and wet cement production process for various fuels and various clinker/cement ratios. Assumptions: Electricity use: 0.38 MJe/kg of clinker; Average emission factor of CO_2 of electricity production: 0.22 kg/MJe. Fuel use (dry process): 3.35 MJ/kg of clinker; (wet process): 5.4 MJ/kg of clinker.

	Process emissions	Process and fuel-related emissions			
Clinker/cement ratio	**Clinker**	**Coal**	**Fuel Oil**	**Natural gas**	**Waste[a]**
Dry process					
55%	*0.28*	0.55	0.50	0.47	0.36
75%	*0.38*	0.72	0.66	0.61	0.47
(Portland) 95%	*0.49*	0.89	0.81	0.75	0.57
Wet Process					
55%	*0.28*	0.67	0.59	0.53	0.36
75%	*0.38*	0.88	0.77	0.69	0.47
(Portland) 95%	*0.49*	1.09	0.95	0.90	0.57

[a] assumed a 100% fuel coverage by waste and a waste CO_2 emission factor of zero. Depending on the alternative waste processing technology, i.e. with or without energy recovery, this factor may be higher, leading to higher nett CO_2 emissions.

3.2.1.2 Important aspects using waste

The following aspects are important considering the use of waste in the cement production:

- Energy efficiency of waste combustion in cement kilns
- Constant cement product and fuel quality
- Emissions to atmosphere
- Trace elements and heavy metals
- Alternative fate of waste
- Alternative waste

These issues are subsequently discussed hereunder.

Energy efficiency of waste combustion in cement kilns

Waste replaces fossil fuels. The energy from waste is recovered in the cement kiln at an efficiency of 75%, but may go as high as 90 to 95%.[1]

[1] Waste is normally recycled, combusted in specialised incincerators or landfilled. In incinerators energy is sometimes recovered. Actual best results obtained for municipal garbage incinerators in the Nordic countries and in Switzerland are about 25% (energy-to-electricity conversion) for net saving. The majority of the hazardous waste incinerators are not equipped for energy recovery.

Constant cement product and fuel quality
To maintain a certain specified quality of the cement, the composition of the raw materials (including the raw material for energy input) should not vary greatly. To ensure stable kiln operation and meet process and quality targets, waste fuels must have a consistent physical and chemical composition and meet the specifications set by the cement plant. Meeting the specifications means that the wastes must be selected and blended prior to use as fuel.

Emissions to the atmosphere
It is important to control emissions from the process. The raw material can affect the sulphur dioxide emissions as well as ammonia and ammonium compounds. Toxic, organic exhaust gas constituents, such as dioxins and furans are not significantly affected by the choice of alternative fuels. The emission levels in the exhaust gases are low. Waste introduced in the burning zone is combusted at a flame temperature of 1800 to 2000 °C. Combustion gas retention time of more than 5 seconds at temperatures above 1200 °C in the rotary kiln will destroy and burn the organic compounds, which are fed to the main flame.[1] The raw meal suspension preheater or the chain system of a wet process kiln act with regard to the combustion gases as a dry exhaust gas cleaning system on basis of the circulation fluidised bed absorber principle with a highly alkaline atmosphere. The emissions of a cement kiln are therefore largely independent of the composition of the fuels fed to the rotary kiln.[2] The emissions of a cement kiln are dominated by the characteristics of the available and used raw material.
According to Scheider and Kuhlmann [1997], the emission concentration of dioxins and furans are extremely low, regardless of the fuel used. The organic constituents in the fuel are practically all destroyed in the rotating kiln, and no changes in the emission concentrations were observed when substitute fuels were used. Also low formation rates were observed in the exhaust gas from the kiln. One important reason for this is that heavy metals with catalytic action are only present in very low concentrations in the exhaust gas from kilns. In addition to this, the residence time in the temperature range, which is critical for the formation of these gases, is extremely short.
Because of the high operating temperatures and the long contact time, potential harmful gases are not formed, destroyed or react with the. The use of alternative fuels normally does not change emission rates as shown in Table 2.10.
The Atomic Energy Corporation (AEC) performed tests to measure any emission of pollutants. The results showed a destruction efficiency of 99.999%, which is a ten times better than the required international standard.

Trace elements and heavy metals:
Trace elements are present in raw materials, primary fuels and alternative fuels. The emission of trace elements from cement production is normally very low. The majority of metals into the kiln system are captured in the clinker or clinker dust. Exceptions are mercury whose average retention has been estimated to be 61% and thallium whose average retention has been estimated at 90%. The presence of these

[1] An incinerator for waste operates typically under lower temperatures (850 °C for non-hazardous waste; 1100 °C for hazardous waste) and lower residence time (>2 sec. above 1200 °C).
[2] Use of waste preserves complementary emission from alternative treatment processes (incineration, landfill).

metals must be carefully controlled. The less volatile metals, for example barium, nickel and vanadium, are captured in the clinker while the more volatile metals, such as lead and cadmium if present in the raw materials or in the waste fuels, will be tend to concentrate in the kiln dust. However, metals in kiln dust are generally present in unleachable form [Anonymous, 1992].
Important and significant for the environment is the form of the trace elements and heavy metals in the end product (their mobility, their availability, and their leachability). Other than the volatile ones, all trace elements and heavy metals from raw materials and fuels fed to the cement kiln (in raw material as well as in fuel) are insolubly embedded in clinker, cement and concrete. Heavy metals which pass into the concrete component via the cement are either present in the hydrated cement - hardened cement paste - or are located in the pore water of the concrete. This results in concentration bandwidths for heavy metals in the finished components, which correspond to the different levels in the raw materials. Only very small quantities are released because of the high capacity of concrete to bind heavy metals and due to its dense pore structure. Degré [1996] suggests that leaching tests done on monoliths are proving the total harmlessness of all cement products, and that all cement products can be used for application for drinkable water.[1]

Alternative fate of waste:
The waste used for cement production would otherwise have been landfilled, incinerated or otherwise processed. In all cases this has additional environmental consequences.
TNO [1997b] made a comparison of environmental impacts of waste processing in wet-cement kiln and specialised combustion plants with energy recovery. They considered four different wastes: spent solvents, filter cake, paint residue and sewage sludge. They concluded that for all four wastes the total environmental impact of the two waste processing methods were approximately equal.[2]

Secondary waste
The cement kiln does not produce (extra) secondary waste. All minerals are absorbed in the clinker substance or kiln dust.

3.2.1.3 Economical aspects on waste co-processing

Waste processing has the following economic impacts:

- Avoided costs for fuel, transport and storage.

[1] Leaching of traces depends on chemical and physical conditions of the material that it captured. In general, chromium, arsenium, molybdenum and barium leach relatively quick [Van der Sloot, 1991]. An important chemical factor is the acidity of the substance. Traces are better fixed in high alkalised material, and leach relatively more easy from acid material. In time, an alkalised atmosphere may shift gradually to a more acid atmosphere [Swaine en Goodarzi, 1995], so that the conditions for leaching may change.
An important physical property that determines the rate of leaching is structure of the pores. In general concrete have a relatively favourable structure for low leaching rates.
To our knowledge no reproducible leaching tests to long-term leaching effects have been performed.

[2] In the calculations of TNO [1997b], the total CO_2 emission from fossil fuels (long carbon cycle) and from the organic fraction (short carbon cycle) are taken into account. For the assessment of CO_2 emissions in relation to global climate change, only the CO_2 released by the long carbon cycle should be taken into account as the short-term are assumed to have a zero nett CO_2 emission effect.

- Avoided costs for processing waste otherwise (incineration, recycling, landfill), including avoided costs for residue handling of waste treatment
- Costs for transport and storage of waste for fuel.
- Costs for waste processing (blending, mixing)
- Costs for extra control (flue gas treatment; inlet) (if needed)
- All indirect costs (process development, communication, etc.)

Generally it can be said that for the use of waste in cement kilns, minor investments are needed. On the other hand, waste treatment costs are avoided.[1]

Degré [1996] concluded that waste management by co-combustion in an existing process as the cement industry is globally much cheaper compared to elimination in dedicated incinerators. Price ratios are in average 1 to 5.

3.2.1.4 Regulatory framework

The use of waste instead of fossil products is constrained by a number of regulations. The regular framework should favour, case by case, the overall environmentally best solution.

The use of as waste specified material as secondary raw material could be in accordance of national and international policies on waste management: increased resource recovery and reduction of the quantities of waste requiring disposal. The classification of these materials as waste, instead of raw material, may raise restrictive regulations from regulatory authorities.
A legally important aspect in the EU is the question whether waste is valorised (beneficially used) or eliminated. This will be discussed more extensively hereunder.

Valorisation or elimination of waste
The differentiation between elimination and valorisation is of importance as regulations distinguish between waste elimination and valorisation. For instance, directives of the European Union allow the export of waste for the purpose of valorisation. Waste is valorised when it is processed in a cement kiln to substitute raw materials and/or fuels. The waste contributes in this way in a positive way to the cement production process. Waste is eliminated when it is combusted in a cement kiln without substantial diminishing of fuel requirements or process improvement.

Approaches used to determine between valorisation and elimination are normally based on the properties as fuel or on the properties as raw material. Few approaches apply an integrated qualification. TNO [1997] suggests the Materials and Energy Potential (MEP) method as a method to determine whether a waste is valorised or eliminated.
An important property of waste is its heating value. In the study of TNO [1997], waste has been regarded as valorised when sufficient energy in the waste is present

[1] Total treatment costs (cost minus benefits; excl. VAT) in Dutch incinerators are 110 $US\$_{1996}$/t waste processed [AOO, 1997].
European average landfill costs are estimated at 22 $US\$_{1993}$/t for rural areas, and 35 $US\$_{1993}$/t for urban areas. [DGXI, 1998].

to produce heat in the kiln above 1500 °C.[1] The temperature requirement can be weakened if the waste can contribute as a source of raw material. The energy potential (E) and the Material potential (M) are both expressed as figures without dimension. The waste is regarded as valorised when the sum of E and M is greater than 1. Table 3.4 shows for various types of waste (i.e. waste consisting of mainly organics, mainly minerals and mixed ones) the valorisation. From the table it can be concluded that a high water content determines to a large extent whether a waste is classified *as eliminated* or *valorised* in a cement kiln.

Table 3.4. Valorisation of waste for recovery in cement kilns [TNO, 1997]. Figures are valid for the wet-cement process with up to 30% water in raw materials fraction and a preheated air inlet temperature of 800 °C. Differences in the outcome between wet and dry process are generally small.

	Unit	HPC	FE	FC	DSS	WSS	PC	LFC
LHV	MJ/kg	25	12.5	6	11	3	16	3
H2O	%	20	20	50	22	70	0	50
Temp. combustion	°C	1873	1702	1311[a]	1688	905	1932	1049
M	-	0	0.70	0.29	0.63	0.16	0.53	0.29
E	-	1.53	1.75	0.96	1.74	0.26	1.93	0.59
Valorisation	-	**yes**	**yes**	**yes**	**yes**	no	**yes**	no

a: the lower combustion temperature under 1500 °C is compensated by the fraction (20%) of usable waste.

HPC: solvents
FE: filtration earth
FC: filter cakes
DSS dry sewage sludge
WSS: wet sewage sludge
PC: poor quality coal
LFC: low quality filter cakes

3.2.1.5 Conclusions and Recommendations

Waste processing in the cement industries is feasible and current practise. Waste as alternative fuel is increasingly used in cement plants. Waste may reduce CO_2 emissions by 0.1 to 0.5 kg/kg cement produced compared to current used production techniques using fossil fuels. The use of waste generates no additional emissions, although care should be taken for high volatile elements as mercury, thallium, cadmium and chlorine. On the other hand, the use of waste does not impair clear environmental advantages, besides the reduction of substituted fossil fuels.

Due to process characteristics, the cement industry can play a role in waste policy.

- high combustion temperature and long residence time
- partly self cleaning process, relatively low emissions
- total recovery of waste mineral parts in valuable goods

Care should be taken that cement manufacturers do not abuse cement as a final storage for heavy metals .

[1] Elimination of waste does not contribute to the firing of heat in the kiln and waste can therefore not be seen as a fuel. For the transport of waste without value different regulation exist compared to waste with value (e.g. as a fuel), amongst others for export/import. Elimination may still be attractive in cement production in case of e.g. hazardous waste disposal.

From a macro-economic point of view, the major interest of waste processing by the cement industry is for employment, financial inputs for the authorities, for global energy savings, and for resources conservation.

Application of waste may be stimulated when the following conditions are fulfilled:

- Assurance of consistent supply of waste
- Commitment of cement plant management, and assurance of quality control
- Public sector approval and enforcement of environmental regulations by government agencies

It is recommended to find joint solutions with authorities or with local waste management systems. This can present favourable opportunities within waste recovery schemes.

Judgement should be made to qualify the waste characteristics in connection with (long-term) clinker/cement/concrete quality. A methodology, for instance as described in the BUWAL Directive [Lang, 1998] should be applied to judge trace elements. Aspects to be considered are maximum acceptable concentration of trace elements at the inlet of the waste management facilities, preparing alternative fuels and raw materials for the cement plant, and maximum acceptable concentration at the inlet of the cement plant.

3.3 BLENDED CEMENTS.

Today, most of the cement manufactured is Portland cement. Portland cement is typically made by intergrinding about 95% clinker and about 5% additives (mainly gypsum, see chapter 2). The production of clinker is the most energy-intensive step in the cement manufacturing process. Because the percentage of clinker in Portland cement is so high, Portland cement is very energy-intensive to manufacture. In addition, cement-related CO_2 emissions are the result of both fossil fuel combustion and the calcination phase of the clinker manufacturing process. One strategy for reducing the energy consumption, energy-related CO_2 emissions, and process-related CO_2 emissions, while making use of waste materials from other industries, is to promote the manufacture and use of blended cements. In blended cement, a portion of the clinker is replaced with industrial by-products such as coal fly ash (a residue from coal burning) or blast furnace slag (a residue from iron making), or other pozzolanic materials (e.g. volcanic material). These products are blended (often interground) with the ground clinker to produce a homogenous product; blended cement.

The performances of blended cements can be similar to those of Portland cement; although blended cements have lower early strength, and thus have a longer curing time, they have higher final strength as well as improved resistance to sulphates and sea water [Cangiano, 1992]. Mineral admixtures improve durability by reducing the permeability of concrete through a more homogenous and dense microstructure that is attributable to the segmentation of large pores and reduction of

both the content and the size of calcium hydroxide crystals in the product [Mehta, 1994].

Cement production practices vary regionally in the amount of additives used. While in Europe, the use of blended cements is quite common it is less common in e.g. North America. The relative importance of additive use can be expressed by the clinker/cement ratio to produce cement in a specific country. Portland cement has a C/C ratio of 0.95, whereas blast furnace slag cement may have a C/C ratio as low as 0.35. Countries like the U.S., Canada and United Kingdom have high C/C-ratios showing the dominance of Portland cement, while countries like Belgium, France and the former Soviet Union show lower C/C ratios, expressing the relatively larger use of blended cements [Worrell, 1995]. Even in countries that already show a relatively large use of blended cement, opportunities may exist to further increase blending, as for example in Japan [Anonymous, 1997]. As no international sources collect clinker production data, it is not possible to accurately estimate the current practices in all cement producing countries. In Chapter 2 we have used a regional estimate on the basis of information of key countries. The most important additives for cement production are blast furnace slags, fly ash, synthetic pozzolans and a variety of other (waste) materials.

Blast Furnace Slag. Blast furnace slag is a by-product of the iron making process in the iron and steel industry. Its main components are calcium oxide and silicon oxide. There are four different types of blast furnace slag: air-cooled, expanded (or light weight), granulated, and pelletised. The differences in these slag types result from the different techniques that are used to cool the slag. Only granulated and pelletised blast furnace slag can be used as cement additives [Detwiler, 1996]. In Europe mostly granulated blast furnace slag is produced, while in the U.S. these slag types account for only a small portion of the slag produced [Worrell, 1995]. As seen in Table 3.5, most of the slag currently produced through iron making in the U.S. is air-cooled.

Table 3.5. Blast Furnace Slag in the U.S.: General Production and Use Characteristics

Type of Blast Furnace Slag	1994 Production (Mt)	Production Characteristics	Primary Uses
Air-cooled	10.7	Molten slag is run into a pit where it cools and solidifies, and then is dug, crushed, and graded for aggregate	coarse aggregate or granular base for e.g. road base
Expanded (or light weight)	1.6	Molten slag is expanded by adding a limited amount of water, which generates bubbles upon evaporation and results in porous slag	Light-weight aggregate
Water-Granulated		Can be produced in two ways (a) pit granulation - molten slag is run into a pit of water, and (b) jet granulation, a modified version of pit granulation - molten slag is broken using high-pressure water jets as it falls into the pit of water	cementitious material in concrete
Pelletised (dry-granulated)		Molten slag is spun over a rotating drum that has fins mounted on it; the fins break the slag into small particles that eventually solidify into pellets	Light-weight aggregate and in slag cement manufacture
TOTAL	**12.3**		

Sources: Detwiler [1996], Hanson and Lynn [1995], Kuennen [1996b] and Lee *et al*. [1996]

The amount of blast furnace slag produced depends on the amounts and quality of the iron ores, coal and limestone used in iron making. Slag is typically produced at a rate of 220 to 370 kg per tonne pig iron [Kalyoncu, 1998b]. There are no regular statistical sources on slag production. Hence, slag production has to be estimated on the basis of pig iron production. In Table 3.6 we estimate the 1991 production in various regions on the basis of pig iron production [IISI, 1992].

Table 3.6. Estimated global blast furnace slag production, by region [1991].

Region	Pig Iron Production (Mtonnes)	Estimated Slag Production (Mtonnes)
Africa	9.8	2.2 – 3.6
Latin-America	28.5	6.3 – 10.5
North America	52.3	11.5 – 19.4
EE/FSU	112.7	24.8 – 41.7
Western Europe	104.2	22.9 – 38.6
India	14.2	3.1 – 5.3
China	64.3	14.2 – 23.8
OECD Pacific	104.1	22.9 – 38.5
Rest of Asia	12.6	2.8 – 4.7
Middle East	2.0	0.4 – 0.7
Rest of World	0.0	0
Total	504.7	111 – 187

Fly Ash. When pulverised coal is burned to generate electricity, large quantities of fly ash are produced. Fly ash is a solid, fine-grained coal-combustion by-product

that is transported in the flue gases from the boiler and collected in mechanical or electrostatic separators. In the U.S. two different (ASTM) classes of coal fly ash are produced - Class C and Class F. Class C fly ash is produced from coal from sub-bituminous and generally has a lime content of 20% or more, which allows it to harden when exposed to moisture. Class F fly ash, from bituminous and anthracite coal, typically has a lime content of less than 10% and thus does not harden until mixed with Portland cement or lime [Buy Recycled Business Alliance 1995].

The amount of usable fly ash depends on the coal type, ash content of the coal used, the combustion process (boiler type), and the fly-ash recovery system. Generally, fly ash is available in sufficient supply in countries using coal-fired power stations. Regional supply and consumption may not always be balanced. In the United States approximately 39 Million tonnes of fly ash (dry, 1996) are produced, of which only 30% is re-used [Kalyoncu, 1998a]. Cement and concrete production in the U.S. was the main use of the fly ash, using nearly 7 Million tonnes (or 18%). The relatively limited application of fly ash in the U.S. shows the large potential for future application, although not all fly ash is suitable for cement production. Other countries, e.g. Brazil, may have limited supply of fly ash, as most power is generated on the basis of hydropower.

Alternative Additives. The main other additives are ground limestone, pozzolanic material, burnt shale, silica fume, or synthetic additives. Slags from steelmaking (electric arc furnace and basic oxygen furnace) contain calcium oxide, but are generally too hard to use for blended cement production. Texas Industries [Midlothian, Texas] uses EAF-slags as input into the clinker kiln, reducing CO_2 emissions, as the limestone is already burnt. The most common alternative additives are natural occurring pozzolans, which are mostly from volcanic origin. Trade in additives is limited, due to the low value added of the additives.

Intergrinding small amounts of limestone with clinker can reduce the clinker need, and hence the GHG emissions, while not influencing the product negatively. Many countries allow the use of up to 5% limestone in Portland cement, including Japan, Canada and Germany. If this would be general practice this would reduce carbon emissions by approximately 5%. However, in the U.S. the Standard Specification does not allow addition of limestone [Cahn, 1997]. Most U.S. cement companies on the ASTM committee are currently trying to change the specification to allow intergrinding of limestone.

3.3.1 Estimates for Carbon Emission Reduction

The future potential for application of blended cements depends on the current application level (or Clinker/Cement ratio), on the availability of blending materials, and on standards and legislative requirements. Worrell *et al*. [1995] tried to estimate the potential for carbon emission reduction on a national basis for 24 countries in the OECD, Eastern Europe and Latin-America. They estimated the minimum availability of blending materials on the basis of pig iron production and coal combustion. The potential emission reduction varied between 0% and 29%. The average emission reduction for all countries (producing 35% of world cement in 1990) was estimated at 22% [Worrell, 1995]. It was 0% for countries with already

a large share of blended cement production (e.g. The Netherlands) or a low availability of blending materials, i.e. countries without iron production or coal fired power stations (e.g. Costa Rica, Guatemala). It is high for countries without much production of blended cements and a well developed industry or fossil based power industry (e.g. United Kingdom, United States) [Worrell, 1995]. The C/C-ratio for China is estimated at 85% [Feng, 1995]. Considering the large iron production (see Table 3.5) and coal use in power production, a large potential for blended cement may also be expected for the World's largest cement maker.

The costs of blending materials depend strongly on the transportation costs, and may vary between 15 and 30 US$/tonne for fly ash and approximately 24 US$/tonne for blast furnace slag. Shipping costs may increase the price significantly, depending on distance and shipping mode. The prices are still lower than the production costs of cement, estimated at approximately 36 US$/tonne (1990) in the United States [Huhta, 1992] (clinker prices may be lower today).

Summarising, the global potential for carbon dioxide emission reduction through producing blended cement is estimated to be at least 5% of total carbon emissions from cement making of 226 Mtonnes C, but may be as high as 20%. The potential savings will vary by country, and even by region. For a better analysis, regional supply and use patterns should be taken into account, as transport costs may inhibit the use of fly ash or slag for cement production. In Europe, cement mixing plants can now often be found near iron makers, as up to 65% of cement can be blast furnace slag according to the ENV 197 standards, transporting the clinker from nearby clinker plants.

3.4 ENVIRONMENTAL ISSUES

Additives like fly ash can contain high concentrations of heavy metals, which may theoretically leach to the environment under unfavourable conditions. In the literature on the effects of slag and fly ash on the structural properties of cement, we found no mention of environmental issues [Gifford and Elliot 1997, Grutzeck and Sarkar 1994, Malhotra 1995, Moukwa, 1993, Swamy 1991]. Only, the use of non-ferrous slags seems to be limited to slag contents of 15% by mass. Although now allowed in the European cement standard ENV 197, it should be noted that some authorities are concerned about the use of non-ferrous slag, as it can contain heavy and potentially toxic metallic species that could be leached out. Therefore, local regulations will have to be checked if non-ferrous slag-containing concrete is used in proximity to watercourses and Dhir [1994]. Leaching of trace (heavy) metals from fly ash is generally a problem in using fly ash in most construction materials [Bowders, 1990, Church, 1995, Creek and Shackelford, 1992]. In the literature the environmental concern was not expressed in the context of blended cements. In fact, the addition of even a little cement reduces leaching of toxics from fly ash dramatically.

However, fly ash and blast furnace slag may be considered hazardous wastes under environmental legislation in some countries, limiting the use of fly ash to specified companies. In the United States fly ash falls under the Resource Conservation and Recovery Act (RCRA), and gives the states the jurisdiction to define fly-ash a hazardous waste. In practice, the state regulation varies greatly across the U.S.

[Jagiella, 1997], limiting the re-use of fly ash. Countries and states should set clear re-use ruling for fly ash and blast furnace slag in cement, to increase the production of blended cements.

3.5 CEMENT STANDARDS AND BUILDING CODES

Cement standards may vary widely between countries. Differences may be found in the allowable clinker content of the cement, chemical composition, strength, setting time, and test procedures used [Jackson and Lawton, 1993]. Worldwide 876 cement standards existed in 1991, and in Western Europe alone 50 different standards exist for blended cements. Only 59 countries had cement standards for blended cement [Cembureau, 1991], meaning that many cement producing and using countries did not have standards, practically blocking the application of blended cements. The introduction of standards in Western-European countries has increased the use of blended cements. Development of standards for blended cements and of the additives is the first step to introduce blended cements in a country.

Also the specification of Portland cement may be a barrier to use of blending materials. Standards in many countries allow intergrinding of up to 5% limestone in Portland, while in other countries (e.g. the United States) this is not allowed [Cahn, 1997]. Intergrinding up to 5% limestone would reduce carbon dioxide emissions with almost 5%, while evidence exists to indicate that the cement quality would not be influenced adversely.

Besides product standards, building codes may be a barrier to application of blended cements. Although blended cements have superior qualities, the setting time is longer than that of Portland cement. Government agencies have often set a code for strength and other properties of concrete for construction projects. Cement specifications and codes influence the energy intensity of the cement used. The main issues are the fineness [Blaine], C_3S alkali content and additives in the cement. Building codes prescribing the strength and setting time may impact the choice of cement type indirectly, and favour the use of Portland cement (due to the longer time needed by blended cements to reach the optimal strength, compared to Portland cement).

Alkali standards are introduced to improve the strength and quality of the cement, and the long-term reaction with specific aggregates. . A low alkali content leads to higher energy losses, as hot partially calcined cement kiln dust is removed from the process. This leads to energy losses, while generating CKD, which may be classified as hazardous waste under the RCRA. Alkali content is influenced by the alkali content of the raw materials used. The opportunity to select low alkali raw materials may be limited by economic factors, as many clinker kilns are located near limestone reserves. Transport costs of limestone are prohibitive in using other limestone reserves. Cement specifications for specific applications may allow higher alkali content, without reducing the quality of the cement or concrete. In Europe cement standards allow typically a higher alkali content, reducing the need for bypassing and increasing the energy efficiency [Holderbank, 1993]. The alkali aggregate effect can also be reduced by using additives to blend the cement. Re-

placing clinker by 50% blast furnace slag addition or 25-40% fly ash, will reduce the alkali content of the cement.

3.6 CONCLUSIONS

The production and use of blended cements is generally seen as an important measure to reduce the carbon dioxide emissions from the cement industry, as evidenced by statements from the industry worldwide, including Canada [CPCA, 1997], Japan [Anonymous, 1997a] and the United States [Cahn, 1997]. The global potential for carbon dioxide emission reduction through producing blended cement is estimated to be at least 5%, but may be as high as 20%. The potential savings will vary by country, and even by region. For a better analysis, regional supply and use patterns should be taken into account, as transport costs may inhibit the use of fly ash or slag for cement production. The major barriers do not seem to be supply or environmental issues, but rather existing product standards and specifications, and building codes.

3.7 ALTERNATIVE CEMENTS

One of the ways to reduce carbon dioxide emissions from cement production is to replace high-CO_2-emission Portland cement by alternative low-CO_2-emission cements. Geopolymers or mineral polymers are an alternative to Portland cement. These materials are based on kaolin, instead of limestone.

3.7.1 Geopolymers

Clinker is made by calcining calcium carbonate (limestone), which releases CO_2 into the atmosphere, leaving calcium oxide as the binding agent. The calcium oxide reacts with silica to form calcium silicates. Mineral polymers can be made from inorganic alumino-silicate compounds. An inorganic polycondensation reaction results in a three-dimensional structure, like that of zeolites. It can be produced by blending three elements, i.e. calcined alumino-silicates (from clay), alkali-disilicates and granulated blast furnace slag or fly ash [Davidovits, 1994]. The cement hardens at room temperatures and provides compressive strengths of 20 MPa after 4 hours and up to 70-100 MPa after 28 days [Davidovits, 1994]. The zeolite-like matrix results in the immobilisation of materials, e.g. wastes. Although geopolymers contain high concentration of alkalis, it does not generate an alkali-aggregate reaction, which can result in significant expansion of the cement matrix [Davidovits, 1993].

Research on mineral polymers was already going on in Eastern Europe and the U.S in the early 1980s. In the 1980s new alkali activated inorganic cementitious compositions were commercially introduced in the United States which resulted from the development carried out on inorganic alumino-silicate polymers or geopolymers [Davidovits, 1985; Heitzmann, 1987]. Geopolymers are, for instance, applied in the automobile and aeronautic industries, non-ferrous foundries and metallurgy, civil engineering, and plastic industries. They were originally developed to create non-flammable plastic materials, based on silica chemistry rather than on carbon chemistry. In a later stage the application of the silica-based material as cement was considered. Mineral polymers can be used for most construction purposes [Malone, 1985] and can also be used to immobilise solid wastes or for the production of reinforced molds [Davidovits, 1991].

CO_2 emissions from the production of mineral polymers are determined by the carbon content of the raw materials and the energy used in the production. The silica-alumina raw materials can be found on all continents. An alternative approach is a blend of Portland and Geopolymer cement. In this way a cement is developed (under the brand name Pyrament) that comprises of 80% Portland cement and 20% Geopolymeric materials. Calcination of the potassium or sodium may result in CO_2 emissions, depending on the geological forms in which it is used as a raw material. Research on geopolymers is still ongoing.

3.7.2 Carbon dioxide reduction potential

As the geopolymers do not use $CaCO_3$ as a basic material, the production of CO_2 is considerably less. The CO_2 emission (non-fuel related) for geopolymers ranges from 0.03 to 0.08 kg/kg cement. This should be compared to 0.30 to 0.55 kg CO_2

per kg Portland cement. It is also argued that the fuel-related CO_2-emission for the production of geopolymers is considerably lower, because it does not require extreme high temperature kilns. The manufacturing of mineral polymers is done at relatively low temperatures. The calcining of alumino-silicates occurs at temperatures of 750 ºC [Davidovits, 1994]. However, no energy consumption data have been found in the literature. The Geopolymer Institute [1998] published a 60% to 70% less energy intensive production for Carbuncles cements (a geopolymeric cement that comprises 75% by weight of geological elements) than for Portland Cement. Overall it is claimed that production of geopolymers produces about 80 to 90% less CO_2 emissions than Portland cement production [Davidovits, 1994].

3.7.3 Economics

According to Davidovits [1994] production of cement based on geopolymers requires a 5 to 10 times lower investment than to produce Portland cement. The energy costs for production are also lower, because considerably less energy is required. Commercially scaled production, comparable to that of Portland cement, does not exist. In the literature no hard data is found on the production costs of geopolymers.

3.7.4 Conclusion

Preliminary results of the Geopolymer Institute indicate that material based on silica instead of calcium may replace Portland(-like) cement. In the case that the material is an integral substitute, it would especially give opportunities to countries with a high growth in demand such as many developing countries. Application of the material may reduce carbon dioxide emissions by 80%. No industrial or engineering estimates of the production of geopolymers have been published yet, stressing the need for research to evaluate the viability of geopolymers as an alternative to cement. Independent research concerning the properties, applicability (long-term durability and resistance) and economics of the material are needed for a solid judgement whether these materials are appropriate to replace conventional cement binders.

3.8 REMOVAL OF CO_2

Reduction of carbon dioxide emissions from cement production can be obtained by applying carbon dioxide removal. In this technique, CO_2 is separated during or after the production process and subsequently stored or disposed of outside the atmosphere. In some cases the recovered No penetration of alternative cements (i.e. cements that do not require calcium carbonate as raw material) have been assumed. The applicability and potential of these cements are at this stage of development not sufficiently known.
can be used for other purposes. The CO_2 removal process can be split into three separate steps: recovery of the CO_2 (often including drying and compressing), transport of the CO_2 to a location where it is handled further, and utilisation, storage or disposal of CO_2.

3.8.1 Storage potential of carbon dioxide

The emission mitigation potential of carbon dioxide removal may be limited by the potential to use the carbon dioxide and by the space available to store it safely and securely. Table 3.7 presents an overview of storage potentials as discussed in the literature.
The potential to utilise recovered carbon dioxide as a commodity is interesting but small. An option, the potential of which is not yet included in the table, might be the use of carbon dioxide for enhanced gas recovery from deep coal beds. The carbon dioxide is used to push the methane out of coal layers. It is argued that for each recovered methane molecule, two molecules of carbon dioxide will be absorbed. Winning of natural gas from coal bed layers using carbon dioxide may result in a 'sink' of carbon. Research to this technology is, amongst others, carried out by researcher of the Alberta Research Council [Gunter, 1998]. They concluded that the more methane could be recovered by using carbon dioxide compared to conventional techniques used.
The potential to store carbon dioxide in depleted oil and natural gas fields is much larger. Estimates range from 130 to 500 GtC, depending on the amount of oil and gas recoverable. The estimated potential for disposal in aquifers ranges from about 90 to over 1000 GtC. A recent comprehensive study for the Joule II programme estimates a storage capacity of 220 GtC for the EU and Norway. The study also concludes that underground disposal is perfectly feasible method of storing very large quantities of carbon dioxide. The carbon dioxide could most probably be retained for millions of years [Holloway, 1996]. Another large potential repository for carbon dioxide are the oceans.

Table 3.7. Low and high estimates of carbon dioxide utilisation and storage options [Turkenburg, 1997]

Utilisation[1]	0.2	1	GtC/a
Exhausted gas wells	90	400	GtC
Oil wells	40	100	GtC
Saline aquifers	90	>1000	GtC
Ocean disposal	400	>1200	GtC

1. Mainly for the use for Enhanced Oil Recovery. Minor contribution for the production of chemicals.

3.8.2 Carbon dioxide removal from cement production

CO_2 is originating in the cement production from two principally different sources: raw material and fuel. Process-related CO_2 is formed during the calcination process, where $CaCO_3$ is converted to CaO and CO_2. The fuel-related CO_2 is formed during combustion of fossil fuels, alternative fuels or biomass. The formed CO_2 originating from the calcination process as well as from the combustion processes leaves the process via the flue gases. Typical CO_2- -concentrations in the flue gases range from 14 to 33% (see Table 2.12, page 31) for concentration ranges for the various cement production technologies.

There are two principal ways to recover CO_2 from production and/or energy conversion processes: integrated in the process or as an add-on technology to the process. These options are discussed in the next sections.

3.8.3 Integrated CO_2-recovery technologies

CO_2 may be recovered by decarbonisation of the fuel. The carbon-free fuel can be used in the cement production process. The recovered CO_2 can be stored or utilised.
Various process alternatives are applicable to convert fuel prior to combustion. Natural gas can be reformed to a mixture of H_2 and CO, which can subsequently be transformed in a mixture of H_2 and CO_2 through the so-called water-shift reaction. Fuel oil and coal can be transformed by gasification into a mixture of mainly H_2 and CO. To obtain a mixture that is not diluted with nitrogen, pure oxygen is required. After cleaning, the remaining gas mixture can be further processed in the same way as mixture obtained after the reforming of natural gas.

Conversion of high-carbon fuel to low-carbon fuels is an expensive process due to large investment costs and high energy penalties. In cement works there will be little opportunities to integrate the conversion process into the cement production process (e.g. the cement production process does not have a steam cycle). Another main disadvantage of this method is that only the fuel-related CO_2 is recovered in this way, which is less than half of the total CO_2 production from cement manufacture.

3.8.4 Add-on CO_2-recovery technologies

A second category of CO_2 recovery techniques is the add-on techniques. In this category the CO_2 is recovered after it is formed in the production process. In the literature various schemes are examined, mainly in relation with electricity production processes. The best studied CO_2-recovery methods from flue gases are: membrane separation process; separation under low-temperature conditions chemical absorption process; and combustion in a CO_2/O_2-atmosphere.

Separation of CO_2 by *membranes* can handle flue gases with low dust concentration only, to avoid damage of the membranes. The membrane method requires considerably amount of electricity. As this electricity is not available at low costs

at cement production plants (in contrary to power plants), this option seems to be relatively expensive. Separation of CO_2 using a *low-temperature* method requires also considerable amounts of electricity and is therefore not an appropriate technique to apply at cement plants. The *chemical absorption* method needs low to medium-temperature heat. For each tonne of recovered CO_2 about 3 to 4 GJ heat is required. This is about the same amount of heat required on average to produce 1 tonne of cement using the dry-process, but about 2 GJ per tonne cement more than the heat loss of the cement production process. Assuming a recovery degree of 50% of the 'normal' heat losses of a cement product (dry-process), at least 2.5 to 3.5 GJ heat of external sources per tonne of recovered CO_2 is required. Unless a nearby heat source with considerable waste heat is available, it will be very expensive to apply the chemical absorption technique to separate CO_2 from flue gases of cement production processes.

The CO_2/O_2 method requires mainly electricity as energy input for the process to produce the oxygen required for the combustion process. As on average less than half of the CO_2 stems from a combustion process (the remaining from the calcination process), considerably less oxygen is therefore required for the recovery of one tonne CO_2, than for a similar process in, for instance, a power generation plant. This CO_2 recovery option by combustion in a CO_2/O_2-atmosphere will be explored in more detail in the next section.

3.8.5 CO_2 recovery by combustion in a CO_2/O_2 atmosphere

The capture of CO_2 from flue gases is hampered by the presence of large quantities of nitrogen in the combustion air. This difficulty is avoided by concentrating the CO_2 before attempting to capture it. One way to achieve a gas with a high CO_2 concentration is to modify the combustion process. In this approach oxygen instead of air is used for the combustion, i.e. the nitrogen diluent is removed in an air separation plant before the fuel is oxidised. A problem in this approach is the high stoichiometric combustion temperatures. This problem can be solved, and even turned into an advantage, by recycling produced CO_2. In this way adding more or less recycled CO2 can control the combustion temperature. The CO_2 in these systems acts as the required temperature moderator. Energy loss is reduced associated with heating the N_2 from ambient temperature to the flue gas exhaust temperature. Burning the fuel in absence of N_2 should also reduce the formation of NO_x. In this set-up an exhaust gas is achieved which is predominantly CO_2.

This approach has been described for power plant boilers [Wolsky, 1985] and experimentally tested at the Argonne National Laboratory [Berry, 1986; Payne, 1987; Wolsky, 1987] and Ishikawahima-Harima Heavy Industries [Nakayame, 1992, Takano, 1993; Okawa, 1996; Kiga, 1996].

In principle this process could be applied to cement production process. A mixture of oxygen and carbon dioxide is fed to the burner in the kiln. The oxygen should be produced in a nearby oxygen plant, the carbon dioxide is recycled from the exhaust of the kiln. In comparison with the original/reference process without recovery of CO_2 a number of process conditions changes. These are shortly discussed hereunder.

Cooling of the cement product by the combustion air. In the reference plant, a cement production facility without CO_2 removal, the product cement is cooled down in a short time (some minutes) from the process temperature (about 1200 °C) to about 100 °C. This is required to give the cement the right properties and not to allow the chemical reactions to revert. The heat is removed by air, recovering at the same time considerably amount of energy. The heating of the combustion air is also required to obtain temperatures high enough for the cement production process (1500 °C).
In the plant equipped with a CO_2/O_2 recovery unit, the mixture of oxygen and recycled CO_2 should fulfil the function of cooling the cement product and energy recovery. The exhaust gases consisting mainly of CO_2 and water leave the chimney at about 130 °C. The gases should be cooled down before they can be used (allowing condensation of water at the same time). This may be done using heat exchangers using cooling water or ambient air. An alternative solution may be to cool the cement to in two stages: in the first stage to a temperature of about 60-90 °C by the recycled-CO_2/O_2 mixture, and in the second stage by ambient air or by CO_2 that is further cooled down by adding cold oxygen from the oxygen plant.

Leakage of gases. Leakage of CO_2 out of the kiln and other parts of the system may cause loss of CO_2 for recovery and diminish the effectiveness of the recovery process. Penetration of air into the system will dilute the CO_2 in the system and will cause the need for extra compression energy, transport and storage capacity for the recovered CO_2. Kilns operate normally at pressures lower than atmospheric. The leakage of air into the system depends on per installation, but is generally limited to a few percent of the airflow in the kiln. Due to the low operating pressure of cement kilns, leakage of CO_2 in the kiln may be very small.

Influence on the cement production process. During the calcination, CO_2 is released from the raw material. When the partial pressure of CO_2 changes, this will probably influence the kinetic and equilibrium of the calcination reaction. Higher partial CO_2 pressure may require a higher temperature for the reaction to complete sufficiently. This may, for instance, cause that a part of the reaction occur in the kiln instead of the pre-calciner (modern installations do have standard this equipment). As the heat transfer is considerably lower in the kiln than in the precalciner, this may cause a substantial drop in capacity of the cement plant.

Start-up of cement production process. A cement plant normally requires 1 or 2 planned stops for maintenance per year. Short unexpected stops may occur much more frequently, up to 100 times per year. Consequently, the full potential of the CO_2 recovery may not be obtained. To reduce losses of CO_2 during start-up, onsite storage of CO_2 may be required to pass the first period when no CO_2 or not enough CO_2 is available from the exhaust to recycle.

Application of pre-calciner. Modern installations use pre-calciners to convert the lion's share of the raw material. The ratio of fuel to the kiln and pre-calciner may vary from 60-40% to 90-10% for installations equipped with a tertiary hot combustion air flow from the kiln to the pre-calciner. Installations with a pre-calciner should be equipped with a second combustion point using recycled CO_2.

Other pollutants in exhaust gas. During combustion process thermal and fuel-related nitrogen oxides are formed. In the absence of practically all nitrogen from air, considerably less nitrogen oxides will be formed due to thermal nitrogen reactions. The formation of sulphur oxides will not be influenced significantly. Practically all pollutants will be captured by the CO_2 recovering process, as the vast majority of the gases will be captured and compressed.

3.8.6 Investment and Energy requirement of CO2 recovery.

Compared to the reference plant, the cement plant equipped with CO_2 recovery using combustion in a CO_2/O_2-atmosphere does have a number of extra investments and energy uses. The main investments are for:

- Installation to cool and dry recovered and recycled CO_2
- Installation to recycle CO_2
- CO_2 compressors
- Oxygen plant
- Storage of CO_2 for back-up
- Adaptation of pre-calciner
- Adaptation of cooling section of cement product
- Savings on De NO_x and $DeSO_x$ installations
- (Transport and storage equipment)

The main energy uses:

- Drying and recycling of CO_2
- Compression of CO_2
- Production of oxygen
- Changes in energy flows in cement plant
- (Transport and storage)

The main energy consuming processes within the CO_2/O_2 removal scheme are the production of oxygen and compression of the recovered CO_2. Less energy is required for drying and recycling, transport and underground storage of the CO_2.

Production of oxygen. There are four applied systems to produce oxygen: cryogenic separation method, the adsorption method, the membrane separation method, and the chemical separation method. The cryogenic separation is generally seen as the most economical one for large oxygen production facilities [Hendriks, 1994; Okawa, 1996].

Oxygen requirement. To burn fossil fuel forming a mixture mainly consisting of CO_2 and O_2, 1 to 1.5 tonne O_2 is needed to form 1 tonne CO_2. 'Light' fossil fuels, like natural gas with a high hydrogen to carbon ratio, need relatively more oxygen, because a part of the supplied oxygen reacts with the hydrogen and is therefore not available for the combustion of carbon to CO_2. More oxygen is needed when impurities as sulphur are present or when nitrogen oxides are formed. These quantities will normally not be very high. As combustion take place in an excess of oxygen, required oxygen for combustion in standard conditions may be 10 to 20% higher than is required for stoichiometric combustion.

For the generation of the power required for the production of the oxygen extra fuel of about 20 to 25% of the total fuel-input in the cement process is required.[1] It should be noted that the extra CO_2 generated for the electricity production should also be accounted for.

Costs for the production of oxygen
The total investment required for large oxygen production plant operating at low pressures is 20,000 US$/tpd production capacity. The annual Operation and Maintenance costs are estimated at 3.6% of the investment costs. The electricity consumption for the production gaseous oxygen is typically 220-275 kWh per tonne of O_2 [Wolsky, 1996]. The optimal purity of oxygen is about 97-98% [Okawa, 1996]

Compression of the recovered CO_2. Compression to 8.10^3 kPa (80 bars) is assumed to be necessary before transport of the recovered CO_2. The compression process is achieved most effectively by alternate compression and cooling of the CO_2 flow. A five-stage compression process seems adequate for the flow at an atmospheric pressure. The work required for compression, with an assumed isentropic efficiency of 85%, amounts to 300 kJe/kg of CO_2, or 750 kJ-fuel/kg CO_2.

Costs of the compressors. The investment costs for a compressor with a capacity of 500 tonne CO_2 per hour, including a water knock-out drum, amount to 34,000 US$ (1992) per tonne/h [Smit, 1992]. Another 80% must be added to these costs for housing, installation and infrastructure.
For the other required installation for the CO_2 recovery installation cost information was not available.

Table 3.8 shows some key figures for CO_2 removal from power plants using combustion in a CO_2/O_2-atmosphere. This table shows for four combinations of fuel (coal and natural gas) and cement/clinker ratio (0.95 and 0.5) the energy use per kg produced cement for the various recovery installations. The recovery of CO_2 is assumed to be 90%. The percentage CO_2 emission avoided varies then from 63 to 66%.

[1] Assumed: emission factor of 0.22 kg/MJe, and 15% excess of oxygen for combustion.

Table 3.8 Key numbers for CO_2 removal from cement plants using CO_2/O_2 combustion.

General basic input					
Energy for oxygen production	MJe/kg O2	2.3			
Energy for compression	MJe/kg-CO2	0.3			
CO2 emission electricity	kg/MJe	0.22			
Excess oxygen for combustion		15%			
Process specific basic input					
Type of fuel		Coal	Coal	NG	NG
Type of process		Dry	Dry	Dry	Dry
Clinker/cement ratio		95%	50%	95%	50%
Oxygen requirement	kg O2/kg fuel	3.4	3.4	4.3	4.3
Recovery degree		90%	90%	90%	90%
Energy needed to produce 1 kg cement with CO2 recovery					
Fuel	MJth	3.18	1.68	3.18	1.68
Electricity (cement prod.)	MJe	0.36	0.19	0.36	0.19
Electricity (oxygen prod.)	MJe	0.76	0.40	0.70	0.37
Electricity (compr. CO2)	MJe	0.24	0.13	0.20	0.10
CO2 data					
CO2 production	kg CO2/kg cement	1.11	0.58	0.94	0.50
CO2 emission	kg CO2/kg cement	0.38	0.20	0.34	0.18
CO2 avoided emission	%	66%	66%	63%	63%

Note: no allowance was made for the energy use for drying and recycling of CO_2

4. DEVELOPMENT OF GREENHOUSE GAS EMISSIONS IN CEMENT PRODUCTION USING SCENARIOS

Global carbon dioxide emissions from cement production in 1994 amounted to 345 MtC. This number comprises 310 MtC of direct emissions from cement plants and **35** MtC of indirect emissions from electricity use, generated elsewhere. The cement industry contributed in 1994 for 5% to the total global carbon dioxide emissions. Cement demand worldwide may grow in the coming decades rapidly. Especially in the developing countries, e.g. China and India, a large increase in cement production is expected. In this chapter an estimate is made to the cement production and carbon dioxide emission growth in 10 regions of the world. For this approach a base line scenario is constructed and two scenarios in which a moderate effort and a high effort to reduce carbon dioxide emissions are described.

4.1 FACTORS INFLUENCING THE CARBON DIOXIDE EMISSIONS FROM CEMENT INDUSTRY

The annual development of carbon dioxide emissions from cement industry is related to the following parameters:

- Production of cement (Mt cement per year)
- (Fossil) fuel energy intensity (MJ/kg cement)
- Carbon intensity fuel (kgC/MJ)
- Electricity energy intensity (MJ/kg cement)
- Carbon intensity electricity generation (kgC/MJ)
- Clinker/cement ratio (-)

There are various ways to reduce the specific CO_2 emissions and the total projected global CO_2 emissions:

- Less production of cement
- Improved energy use (fuel efficiency; electricity efficiency)
- Shift to more energy efficient process (wet process → dry process)
- Shift to less carbon intensive (fossil) fuels or to short-cycle carbon-based fuels (biomass)
- Shift to alternative fuels
- Shift to lower clinker/cement ratio
- Shift to alternative types of cement
- CO_2 removal

Based on these parameters a base line scenario and two CO_2 emission reduction scenarios are constructed. These scenarios are discussed in the next sections.

4.2 BASE LINE SCENARIO

The development of CO_2 emissions from the cement industry in the base line is related to the development of the production of cement only. For all other parameters

the 'frozen efficiency' approach is applied, i.e. consolidated energy efficiency, fuel use, clinker/cement ratio, etc.

Historically, the development of the cement production has often been correlated to the growth of the Gross Domestic Product. This tendency can especially be seen in countries and regions in development. This correlation is much weaker (or not present) for high-developed regions as Western Europe and North America. The production growth of cement in these two regions has been low (or even negative) for the last decades. Countries as China and India do show a very high growth rate, especially in the period with high economic growth.
For the construction of the base line to the year 2020 the world has been divided in three subparts: developed regions with no or very limited growth of cement production (Western Europe and North America); (semi-)developed regions with moderate correlation of cement production with GDP development (former USSR, Eastern Europe, OECD pacific), and developing countries with high correlation's of cement production with GDP (Asia, Middle East, Africa, and Latin America). The development of GDP for the 10 regions is taken from the base line A scenario of the IPCC [1996].

Figure 4.1 shows the development of the CO_2 emissions for the base line scenario. Under the base line assumptions the CO_2 emissions from cement production will grow by 90% from an initial 345 MtC in 1995 to 652 MtC in 2020.

4.3 SCENARIO-1: MODERATE EFFORT

The first scenario is based on a 'moderate' effort to reduce carbon dioxide emissions. The following reduction measures are assumed:

- Gradually all regions shift to the most energy efficient process (dry-process with pre-calcination), with an energy use of 3.2 MJ/kg clinker. This convergence of energy efficiency signifies for regions with relatively inefficient processes a higher effort than regions already having a high share of efficient processes. In scenario-1, this convergence is assumed to take place in 65 years. This means an energy efficiency improvement rate varying from 0.3%/yr (OECD pacific) to 1.3%/yr.
- An annual electricity efficiency improvement of 1%. This figure could be obtained by application of a combination of energy efficiency measures as described in Annex 1, and by improving reducing the carbon dioxide emissions from electricity generation, by efficiency improvement and shifting to renewable energy sources.
- An annual decarbonisation rate of fuel of 2%. A combination of fuel shift from coal to natural gas, and additional use of alternative fuels could for instance, obtain this figure.
- Decrease of global average of clinker/cement ratio of 0.88 in the base year 1995 to 0.75 in 2020.
- No penetration of alternative cements (i.e. cements that do not require calcium carbonate as raw material) have been assumed. The applicability and potential of these cements are at this stage of development not sufficiently known.

Figure 4.2 shows the development of the CO_2 emissions for scenario-1. Under the scenario-1 assumptions the CO_2 emissions from cement production will grow by 44% from an initial 345 MtC in 1995 to 498 MtC in 2020. Fuel-related emission will grow by 6%, while process emissions will grow by 76%.

4.4 SCENARIO-2: HIGH EFFORT

The second scenario is based on a 'high' effort to reduce carbon dioxide emissions. The following reduction measures are assumed:

- Gradually all regions shift to the most energy efficient process (dry-process with pre-calcination), with an energy use of 3.0 MJ/kg clinker. This convergence of energy efficiency signifies for regions with relatively inefficient processes a higher effort than regions already having a high share of efficient processes. In scenario-2, this convergence is assumed to take place in 45 years. This means an energy efficiency improvement rate varying from 0.7%/yr (OECD pacific) to 2.2%/yr.
- An annual electricity efficiency improvement of 2%. This figure could be obtained by application of a combination of energy efficiency measures as described in Annex 1, and by improving reducing the carbon dioxide emissions from electricity generation, by efficiency improvement and shifting to renewable energy sources.
- Annual decarbonisation rate of fuel of 3%. A combination of fuel shift from coal to natural gas, additional use of alternative fuels, and implementation of CO2-removal could for instance, obtain this figure.
- Decrease of clinker/cement ratio of 0.88 in the base year 1995 to 0.65 in 2020.
- No penetration of alternative cements (i.e. cements that do not require calcium carbonate as raw material) have been assumed. The applicability and potential of these cements are at this stage of development not sufficiently known.

Figure 4.3 shows the development of the CO_2 emissions for scenario-1. Under the scenario-1 assumptions the CO_2 emissions from cement production will grow by 26%, from an initial 345 MtC in 1995 to 434 MtC in 2020. Fuel-related emission will decrease by 21%, while process emissions will grow by 71%.

Figure 4.4 shows the development of CO_2 emissions (energy-related, process-related and total) following the base line scenario, scenario-1 and scenario-2.

4.5 CONCLUSIONS

Carbon dioxide emissions from cement production contribute significantly to total global carbon dioxide emission. Emissions may grow substantially in the short and long-term period. In a 'frozen efficiency' base line scenario, carbon dioxide emission may almost double in the next 25 years from 345 MtC in 1995 to 652 MtC in 2020. A 'moderate' effort (scenario-1) reducing the projected base line emissions may reduce *the increase* of the emissions to about 44%. The share of process-related emissions will become relatively higher, because fewer measures are available to decrease process-related emissions. In a 'high' effort scenario (scenario-2), assuming considerable improvements, emissions may grow still by 26%. In this scenario emission related to fuel use will decrease by 21%, while process-related

emissions grow by 71%. The relative share of the fuel-related emissions will decrease from the present 45% to 34% (scenario-1) or to 28% (scenario-2). The share of process-related emissions increase from the present 46% to 57% (scenario-1) or to 63% (scenario-2).

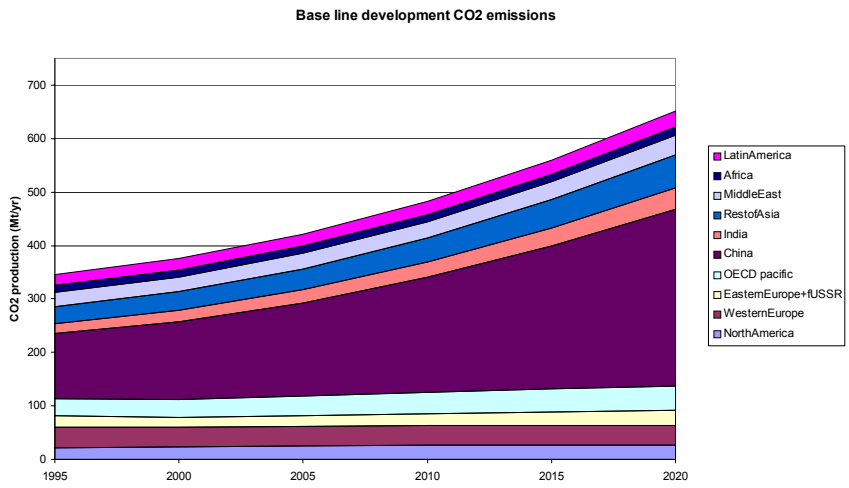

Figure 4.1. Base line CO_2 emissions 1995 to 2020.

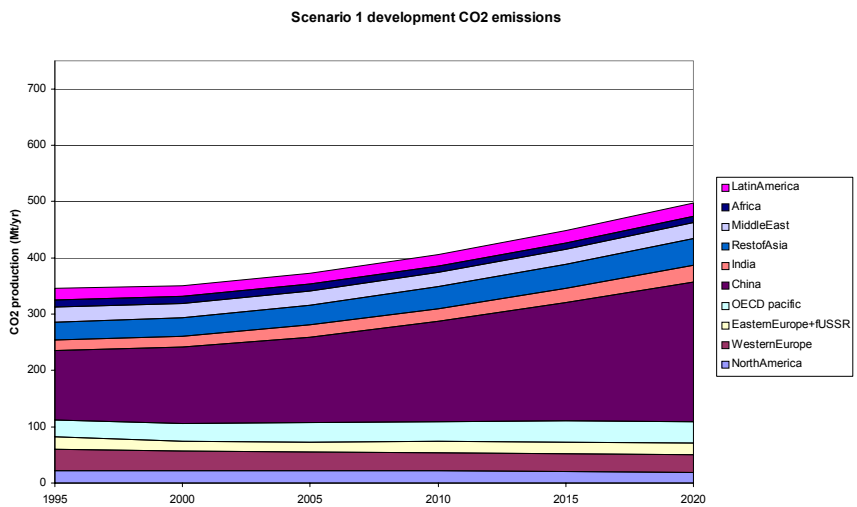

Figure 4.2 CO_2 emissions following scenario-1.

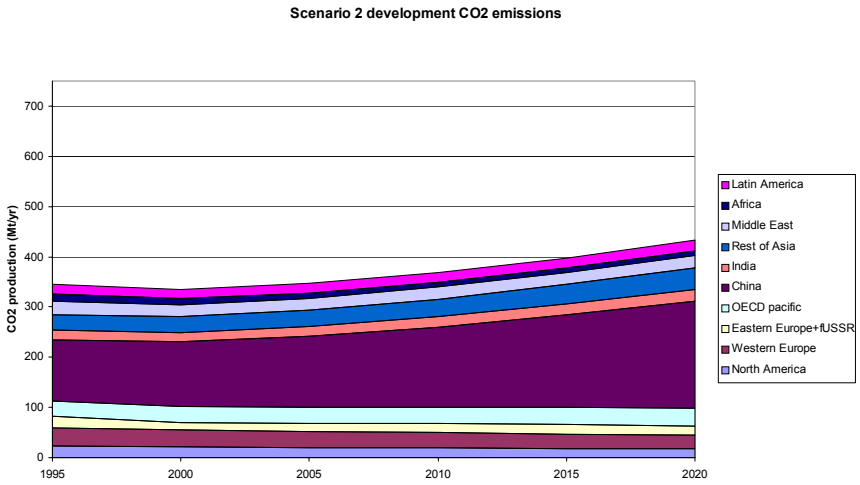

Figure 4.3 CO_2 emissions following scenario-2.

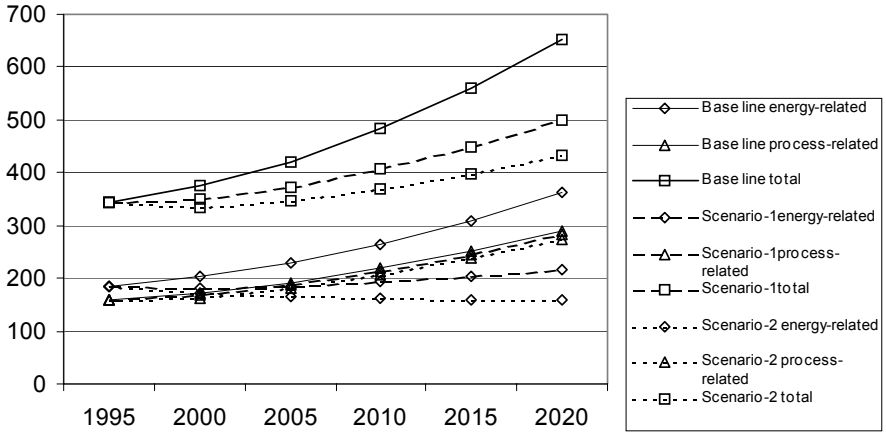

Figure 4.4 Development of CO_2 emissions (energy-related, process-related and total) following the base line scenario, scenario-1 and scenario-2.

Table 4.1 Development of CO_2 emissions following scenario-2.

CO2 emissions related to:	***total***	**fuel**	**process**	***total***	**fuel**	**process**	***total***
Emission in MtC	*1995*	2010	2010	*2010*	2020	2020	*2020*
North America	*22.5*	6.9	10.5	*19.6*	4.7	11.6	*17.1*
Western Europe	*37.0*	9.4	19.1	*29.9*	6.8	19.1	*27.1*
Eastern Europe+fUSSR	*22.2*	5.6	8.6	*17.6*	4.7	13.6	*19.2*
OECD pacific	*31.0*	9.2	18.1	*32.7*	7.8	24.4	*34.2*
China	*122.3*	61.8	53.9	*159.8*	66.3	123.2	*212.9*
India	*19.3*	7.8	8.0	*21.1*	7.3	14.4	*24.8*
Rest of Asia	*31.0*	11.7	16.1	*34.9*	11.0	29.0	*42.3*
Middle East	*26.6*	7.0	13.4	*23.5*	5.6	17.5	*24.7*
Africa	*13.0*	3.7	4.6	*9.8*	3.1	5.7	*10.2*
Latin America	*20.1*	5.7	11.1	*19.1*	4.9	15.7	*21.4*
High developed	*91*	26	48	*82*	19	55	*79*
Less developed	*254*	103	116	*286*	103	219	*355*
World	*345*	129	163	*368*	122	274	*434*

5. CONCLUSIONS

In 1994 cement industry consumed 6.6 EJ of primary energy, corresponding with 2% of world energy consumption. Worldwide 1126 Mt CO_2 or 5% of the CO_2 production originates from cement production. Following a base line scenario, based on the relation of GDP and cement production, global cement production may almost be doubled in 2020 with respect to 1995.
The carbon intensity of cement making amounts to 0.22 kgC/kg cement. In India, North America, and China the carbon intensity is about 10-20% higher than on average. Specific carbon emissions range from 0.10 kg to 0.30 kgC/kg cement mainly depending on type of process, clinker/cement ratio and fuel used. On average a little above 50% of the emissions originates from the calcination step.
To reduce the carbon intensity the following options are identified: improving energy efficiency, shifting to more energy efficient process, shifting to less carbon-intensive fuels or fuels containing short-cycle carbon like biomass, use of alternative fuels, shifting to lower clinker/cement ratio, shifting to mineral polymers, and removal of CO_2.

Seventeen different energy efficiency improvement options are identified. The improvement ranges from a small percentage to more than 25% per option, depending on the reference case (i.e. type of process, fuel used) and local situation. The use of alternative fuels instead of fossil fuel may reduce CO_2 emissions by 0.1 to 0.5 kg CO_2/kg cement (varying from 20 to 40%). On average blended cements may reduce carbon emissions from 0.81 kg CO_2 to 0.64 kg CO_2 per kg cement (20%). Global potential of blended cements reducing carbon emissions is at least 5% but it is estimated to be as high as 20%. An end-of-pipe technology to reduce carbon emissions may be CO_2 removal. Probably the main technique is combustion under oxygen while recycling CO_2. This technique may reduce up to 65% of the CO_2 emissions of a cement plant. However, considerably research is required to assess the unknown aspects of this technique in clinker making. Table 5.1 gives an overview of the identified options to reduce carbon dioxide emissions. The table gives an indication of the reduction potential in a cement plant and a cost range the option can most probably can be implemented.

Table 5.1. Overview of carbon dioxide reduction options

	CO_2 emission reduction potential		Costs (US$/t CO_2 avoided)	Remarks/main issues
	plant-based[a]	Global[a]		
Efficiency improvement measures	0-20%	20%	Benefits to high costs	Various measures
Shift to Dry process Pre-Calciner Kilns	20-40%	10-15%	Retrofitting: 50-150 New: benefits to low costs	Compared to wet process
Shift to low carbon fuels	10-20%	15%	25-50	Application depending on availability of NG and competitive use of NG
Application of waste fuels	20-40%	30%	Benefits to small costs	Restricted by availability, quality demands, regulation, standards, public acceptance
Increasing use of additives in cement	0-65%	30-35%	Benefits	Restricted by availability, quality demands, national standards
Alternative cements	n.a.	80%		Limited information available
CO_2-removal	60-65%	-	50-250	Early stage of technology development

a. These percentages are not additive. Global technical carbon dioxide emission reduction potential for the options 'dry processes + shift to low carbon fuels + application of waste + increased use of additives' is approximately 60%.

Implementation of a set of carbon dioxide emission reduction options will reduce emissions compared to the projected base line emissions. A set of emission reduction options comprising a 'moderate' effort (scenario-1) may reduce the increase of the emissions in 2020 to 60%. A 'high' effort set of options (scenario-2) may reduce the increase of emissions to 35%. It can be concluded that even with stringent reduction measures, global carbon dioxide emissions from cement production will still grow. This is mainly due to the high projected growth of cement production and the low potential available to reduce process-related carbon dioxide emissions.

Acknowledgement
The authors would like to thank the following people for the constructive comments on the draft version of this report: Mr. Hjorth of Cembureau (Brussels, Belgium), Ann Dougherty and Greg Miller of the Portland Cement Association (Skokie, IL, USA) and Michael Nisbet of JAN Consultants (Montreal, Canada);

6. REFERENCES

AAO, 1997, *Financieel-economische analyse van afvalverbrandingsinstallaties*, Aval Overleg Orgaan, Utrecht, the Netherlands

Alsop, P.A. and J.W. Post, 1995. *The Cement Plant Operations Handbook* (first edition), Tradeship Publications Ltd., Dorking, UK

Anonymous, 1986. *Germany, West*, Rock Products April :41.

Anonymous, 1992. *All Fired Up. Burning Hazardous Wastes in Cement Kilns.* Environmental Toxicology International, Seattle, Washington.

Anonymous, 1994. *Cement Plant Modernization in Central Europe*, World Cement 11 25 pp.35-38 (1994).

Anonymous, 1997a. *Building a Cleaner Future in Japan*, *Asian Cement*, January 1997, p.31

Anonymous, 1997b. *China's Cement Industry in 1996 and Development Prospects for 1997*, World Cement **28**: 5-8.

Anonymous, 1998. *Indian Cement Faces Some Challenges: But Potential For Growth Still Massive*, International Cement Review Jan: 36-43.

Bösche, A., 1993. *Variable Speed Drives in Cement Plan*ts, World Cement 6 24 pp.2-6 (1993).

Bowders, John J., Jr., James S. Gidley, and Mumtaz A. Usmen. 1990. *Permeability and Leachate Characteristics of Stabilized Class F Fly Ash*, Transportation Research Record 1288: 70-77.

Bundesverband der Deutschen Zementindustrie e.V., 1997, *Zement 96/97 Zahlen und Daten*, Germany.

Buy Recycled Business Alliance. 1995. *Buy Recycled Coal Fly Ash*. Alexandria, VA: Buy Recycled Business Alliance and the National Recycling Coalition.

Buzzi, S. and G. Sassone, 1993. *Optimization of Clinker Cooler Operation*, Proc. VDZ Kongress 1993: "Verfahrenstechnik der Zementherstellung" Bauverlag, Wiesbaden, Germany (pp.296-304).

Buzzi, S., 1997. *Die Horomill® - Eine Neue Mühle für die Feinzerkleinerung*, ZKG International 3 50 pp.127-138 (1997).

Cahn, D., Greer, W., Moir, R., *Atmospheric CO_2 and the US Cement Industry*, World Cement 8 **28**, pp.64-68 (August 1997).

Canadian Industrial Energy End-Use, 1997, *Development of Energy Intensity Indicators for Canadian Industry 1990-1996*, CIEEDAC, Simon Fraser University, Brunaby, Canada

Canadian Portland Cement Association, 1997. *Cement, Concrete and Climate Change*, CPCA, Toronto, 1997.

Cangiano, S., G. Castaldi, U. Costa, G.P. Tognon, 1992. *Modern Composite Cements: Enhanced Technical Properties, Lower Energy Demand*, Proceedings European Seminar on Improved Technologies for the Rational Use of Energy in the Cement Industry, Berlin, Germany, 26-28 October 1992.

Case jr, H.G., and V.K. Batra, 1997, *Utilisation of waste-derived fuels in cement kilns*, International Cement Journal.

CBS, *Kwartaalberichten Milieustatistieken 1998-II*, jaargang 15, nO_2, Centraal bureau voor de Statistiek, Voorburg/Heerlen 1998

Cembureau, 1989. *European Annual Review no. 12 / 1989-1990, Cement Industry & Market data*, Brussels: Cembureau.

Cembureau, 1997. *Best Available Techniques for the Cement Industry*, Brussels: Cembureau.

Cembureau, 1991. *Cement Standards of the World*, Cembureau, Brussels, Belgium.

Cembureau, 1996. *World Cement Directory*, Brussels: Cembureau.

Cembureau, 1997. *European Annual Review Cement Industry & Market Data*, No 18, July 1997, Brussels, Belgium

Cembureau, 1998. *World Statistical Review No.18, World Cement Market in Figures 1913/1995*, Cembureau, Brussels, Belgium.

Cembureau, 1998b. *Climate Change, Cement and the EU,* Cembureau, Brussels, Belgium

Central Statistical Organization, 1995. *Annual Survey of Industries 1993-1994,* Factory Sector, vol. IX, Calcutta, India (CD-ROM)

Church, D. Andrew, Lufti Raad, and Mark Tumeo. 1995. *Experimental Study of Leaching of Fly Ash,* Transportation Research Record 1486: 3-12.

Cohen, S.M., 1992. *Fluid Bed Cement Clinker Applications*, Proc. 1992 IEEE Cement Industry Technical Conference XXXIV, Dallas, TX, May 10-14, 1992, Institute of Electrical and Electronics Energineers Inc. New York, NY, USA (pp.279-301).

Cohen, S.M., 1993. *Fluid-Bed Cement Clinker Applications*, Proc. VDZ Kongress 1993: "Verfahrenstechnik der Zementherstellung" Bauverlag, Wiesbaden, Germany (pp.342-351).

Cohen, S.M., 1995. *Anwendungsmöglichkeiten der Wirbelschicht bei der Zementherstellung*, Zement-Kalk-Gips 1 48 pp.8-16 (1995).

Conroy, G.H., 1997. *Industrial Application and Results of Low NO_x Precalciner Systems*, World Cement 7 28 pp.6369 (July 1997).

CowiConsult, March Consulting Group and MAIN, 1992. *Energy Technology in the Cement Industrial Sector*, Report prepared for CEC - DG-XVII, Brussels, April 1992.

Creek, Danial N., and Charles D. Shackelford. 1992. *Permeability and Leaching Characteristics of Fly Ash Liner Materials*, Transportation Research Record 1345: 74-83.

Crosilla, F. and H. Häutle, 1997. *Modifying the Hot Gas Circuit in LEPOL Grate Preheaters*, World Cement 3 28 pp.14-20 (March 1997).

Davidovits, J., 1991. *Geoploymers: Inorganic Polymeric New Materials*, Journal of Thermal Analysis 37 pp.1633-1656 (1991).

Davidovits, J., 1993. *Geoploymer Cements to Minimize Carbon-Dioxide Greenhouse-Warming*, in: M. Moukwa, S.L. Sarkar, K. Luke and M.W. Grutzeck (eds.) "Cement Based Materials: Present, Future, and Environmental Aspects", Ceramic Transactions 37 pp. 165-182 (1993).

Davidovits, J., 1994, *Properties of Geopolymer Cements*, Geopolymer Institute, Saint-Quentin, France

Davidovits, J., 1994. *Global Warming Impact on the Cement and Aggregates Industries,* World Resource Review 6(2) pp.263-278 (1994).

Davidovits, J., 1996, *From Ancient Concrete to Geopolymers*, Geopolymer Institute, Saint-Quentin, France

Detwiler, Rachel, Javed Bhatty, and Sankar Bhattacharja. 1996. *Supplementary Cementing Materials for Use in Blended Cements*. Skokie, Illinois: Portland Cement Association.

DGXI, 1998, Personal Communication, May 1998.

DGXII, 1996, *Energy and waste forum - Consensus paper final draft* - June 1996, Directorate General DGXII, EC, Brussels, Belgium

Dhir, R.K. 1994. *Additional Materials and Allowable Contents in Cement*. In Proceedings of the Euro-Cements: Impact of ENV 197 on Concrete Construction, the National Seminar, University of Dundee, September 15, 1994, pp. 57-68.

Duda, W.H., 1985. *Cement Data Book, International Process Engineering in the Cement Industry* (3rd edition), Bauverlag Gmbh., Wiesbaden, Germany.

Duplouy, A. and J. Trautwein, 1997. *Umbau und Optimierung der Drehofenanlagen im Werk Karsdorf der Lafarge Zement Gmbh*, ZKG International 4 50 pp.190-197 (1997).

Dutton, J., 1997. *Kickstart Into Action*, International Cement Review May: 14-26.

Energy Information Administration, U.S. Dept. of Energy, 1997. *Manufacturing Consumption of Energy, 1994*, Washington, DC: DOE/IEA.

Energy Technology Support Unit, 1988. *High Level Control of a Cement Kiln*, Energy Efficiency Demonstration Scheme, Expanded Project Profile 185, Harwell, United Kingdom.

Feng, L., M. Ross, and S. Wang, 1995. *Energy Efficiency of China's Cement Industry,* Energy, the International Journal 7 **20** pp669-681 (1995).

Folsberg, J., 1997. *Future Grinding*, Asian Cement, January 1997, pp.21-23.

Fujimoto, S., 1993. *Modern Technology Impact on Power Usage in Cement Plants*, Proc. 35th IEEE Cement Industry Technical Conference, Toronto, Ontario, Canada, May 1993.

Geopolymer Institute, 1998, *Information on website http://www.insset.u-picardie.fr/geopolymer/ongoing3a.html*, (July 1998)

Gifford, P.M., and J.E. Elliot. 1997. *Behaviour of Mortar and Concrete Made With Activated Blast Furnace Slag Cement*, Canadian Journal of Civil Engineering 24: 237-249.

Grutzeck, Michael, and Shondeep Sarkar (editors). 1994. *Advances in Cement and Concrete (Papers presented at an Engineering Foundation Conference, Unversity of New Hampshire, Durham, NH, July 24-29, 1994)*. U.S.: American Society of Civil Engineers. 621 pp.

Gunter, W.D., T. Gentzis, B.A. Rottenfusser and R.J.H. Richardson, 1997. *Deep Coalbed Methane in Alberta, Canada: A Fuel Resource with the Potential of Zero Greenhosue Gas Emissions,* Alberta Research Council, Alberta, Canada.

Hanson, Douglas, and Cynthis Rorex Lynn. 1995. *Study to Improve Asphalt Mixes in South Carolina (Volume 2 - A Study of Crushed Slag Aggregates in Hot Mix Asphalt)*. Auburn University, Alabama: National Center for Asphalt Technology. Prepared for the South Carolina Department of Transportation. November.

Hargreaves, D., 1997a. *Won Up, Won Down: Turbulent Asian Markets Likely to Have Repercussions on the South Korean Cement Sector*, International Cement Review Dec: 14-20.

Hargreaves, D., 1997b. *Egypt's Economic Growth Boosts Cement Markets: Cement Investment Fever Shows No Sign of Easing*, International Cement Review Nov: 37-45.

Hargreaves, D., 1998. *Indian Cement Faces Some Challenges*, International Cement Review, January 1998, pp.36-43.

Hargreaves, D., ed., 1996. *The Global Cement Report*, 2d edition. Surrey, UK: Tradeship Publications Ltd.

Haspel, D., and W. Henderson, 1993. *A New Generation of Process Optimisation Systems*, International Cement Review, June 1993, pp.71-73.

Heijningen, R.J.J., J.F.M. Castro, and E. Worrell (eds.), 1992. *Energiekentallen in Relatie tot Preventie en Hergebruik van Afvalstromen*, NOVEM/RIVM, Utrecht/Bilthoven, The Netherlands.

Heitzmann, R.F., M. Fitzgerald, J.L Sawyer, 1987, *Hydraulic Cement and Composition employing the same*, US Patent 4,642 137

Holderbank Consulting, 1993. Present and Future Energy Use of Energy in the Cement and Concrete Industries in Canada, CANMET, Ottawa, Ontario, Canada.

Holloway, S. (ed.), 1996. *The Underground Disposal of Carbon Dioxide,* EC-Joule II programme, British Geological Survey, Nottingham, United Kingdom, 1996.

Hudson, J., 1997. *Thailand's Economy – Novermber 1997*, International Cement Review Dec: 30.

Huhta, R.S., 1992. *Operating Costs of U.S. Cement Plants*, Rock Products, November 1992, pp.30-34.

Instituto Nacional de Estadistica Geografia e Infrmatica, 1998. *Indicadores de la Actividad Industrial*. Aguaxcalientes, Mexico: INEGI.

International Energy Agency, 1993 and 1997. *Basic Energy Statistics and Balances*. Paris: IEA.

International Iron and Steel Institute, 1992. *Steel Statistical Yearbook 1992,* IISI, Brussels, Belgium.

IPPC, 1996. *Climate Change 1995 – Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, UK

Jackson, P.J., and J.M. Lawton, 1993. *International Development of Standards for Cements,* Cement, Concrete, and Aggregates 2 **15** pp.149-155 (1993).

Jagiella, D., *Regulatory Requirements: Coal Combustion By-Product Reuse* Paper presented at Workshop and Construction Demonstration for Use of Fly Ash and

Other Coal Combustion Products in Concrete, Howard & Howard Attorneys, Peoria, Illinois, September 16, 1997.

Kalyoncu, R.S., 1998a. *Coal Combustion Byproducts*, U.S. Minerals Yearbook, U.S. Geological Survey, Washington, DC, 1998.

Kalyoncu, R.S., 1998b. *Slag – Iron and Steel,* U.S. Minerals Yearbook, U.S. Geological Survey, Washington, DC, 1998.

Korean Cement Industry Association, 1997, Personal Communication. November, 1997.

Kreisberg, A., 1993. *Selection and Application of Roller Press for Raw Meal Preparation at Alpena*, Proc. KHD Symposium '92, Volume 1 "Modern Roller Press Technology", KHD Humboldt Wedag, Cologne, Germany (1993).

Kuennen, Tom. 1996. *'Waste' Works Wonders: Limited Availability Doesn't Slow Demand for Ground Granulated Blast Furnace Slag*, Concrete Products June: 50-54.

Lang, 1998. Personal communications, Holderbank, Switserland.

Lee, Kwan-ho, Charles Lovell, and Rodrigo Salgado. 1996. *The Use of Pyrolyzed Carbon Black as an Additive (Part III: Air-Cooled Furnace Slag), Final Report*. West Lafayette, IN: Purdue University. November 20.

Malhotra, V.M. (editor). 1995. *Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete: Proceedings of the Fifth International Conference*. Milwaukee, WI: American Concrete Institute.

Malone, P.G., C.A. Randal, T. Kirkpatrik, 1985. *Potential for Use of Alkali-Activated Silico-Aluminate Binders in Military Applications*, (Report WES/MP/GL-85-15), Corps of Engineers, Vicksburg, MI, USA.

Marciano jr, E, and Y. Kihara, *Looking green*, the Brazilian Portland Cement Association, World Cement, April 1997

Marciano, E., and Kihara, Y., 1997. *Looking Green*, World Cement **28**: 82-88.

Marland, G., Boden, T. and Brenkert, A. 1998 "*Revised Global CO_2 Emissions from Fossil Fuel Burning, Cement Manufacture, and Gas Flaring, 1751-1995*," Oak Ridge, TN: Carbon Dioxide Information and Analysis Center, Oak Ridge National Laboratory.

Mehta, P. K. 1994. *Mineral Admixtures for Concrete: An Overview of Recent Developments*. In Proceedings of the Advances in Cement and Concrete, and Engineering Foundation Conference, University of New Hampshire, Durham, NH, July 24-29, 1994, pp. 243-256.

Ministry of Mines and Energy, Secretariat of Energy, 1997. *Brazilian Energy National Balance, 1997*. Brasilia: Ministry of Mines and Energy.

Moukwa, Mosongo, Shondeep Sarkar, Karen Luke, and Michael Grutzeck (editors). 1993. *Ceramic Transactions, Cement-Based Materials: Present, Future, and Environmental Aspects - Proceedings of the Cements Division meeting at the 95th Annual Meeting of the American Ceramic Society (Cincinnati, OH, April 18-22, 1993), Volume 37*. Westerville Ohio: The American Ceramic Society. 202 pp.

Nadel, S., M. Shepard, S. Greenberg, G. Katz and A. de Almeida, 1992. *Energy Efficient Motor Systems: A Handbook on Technology, Program and Policy Opportunities*, ACEEE, Washington, D.C., USA.

Office of Technology Assessment, 1993. *Industrial Energy Efficiency*, (OTA Report E-560), Washington, D.C., USA.

Otero, D.R.I., 1997. *The Cement Industry in Spain*, World Cement **28**: 13-16.

Patzelt, N., 1993. *Finish Grinding of Slag*, World Cement 10 24 pp.51-58 (1993).

Peikang, R., C. Yuanshen, Z. Yuhui, and Z. Qingshan, 1997. *China's Cement Industry in 1996 and Development Prospects for 1997*, World Cement 6 28 pp.5-8 (1997).

PCA, 1996. *U.S. and Canadian Portland Cement Industry: Plant Information Summary*. Skokie, IL: Portland Cement Association.

Rajbhandari, C.D., 1995. *Modern Vertical Shaft Kiln Technology*, World Cement 1 26 pp.65-67 (1995).

Roy, R., 1998. *Continued Growth in US Cement Imports*, International Cement Review Jan: 57-60.

Salzborn, D. and A. Chin-Fatt, 1993. *Operational Results of a Vertical Roller Mill Modified with a High Efficiency Classifier*, Proc. 35th IEEE Cement Industry Technical Conference, Toronto, Ontario, Canada, May 1993.

Sauli, R.S., 1993. *Rotary Kiln Modernization and Clinker Production Increase at Testi Cement Plant of S.A.C.C.I. Spa., Italy*, Proc. KHD Symposium '92, Volume 2 "Modern Burning Technology", KHD Humboldt Wedag, Cologne, Germany.

Secretaria de Energia, 1997, *Balance Nacional de Energia 1996*, SE, Mexico, D.F.

Seebach, H.M. von, E. Neumann and L. Lohnherr, 1996. *State-of-the-Art of Energy-Efficient Grinding Systems*, ZKG International 2 49 pp.61-67 (1996).

Sinton, J., 1996, "*Energy efficiency in Chinese Industry: Positive and Negative Influences of Economic Systems Reforms*", Ph. D. Thesis, University of California, Berkeley, pp. 55-74.

Sinton, J., 1996. *Energy Efficiency in Chinese Industry: Positive and Negative Influences of Economic Systems Reforms*, Ph.D. Thesis, University of California, Berkeley.

Sloot, H.A. van der, 1991. *Systematic leaching behavior of trace elements from construction materials and waste,* In: J.J.J.M Goumants *et al*. (eds), Waste materials in construction, Elsevier Science Publishers, Amsterdam

Somani, R.A., S.S. Kothari, 1997. *Die Neue Zementlinie bei Rajashree Cement in Malkhed/Indien*, ZKG International 8 50 pp.430-436 (1997).

Su, L-H., 1997. *TPI Polene, An Operational View,* International Cement Review, December 1997, pp.28-40.

Süssegger, A., 1993. *Separator-Report '92*, Proc. KHD Symposium '92, Volume 1 "Modern Roller Press Technology", KHD Humboldt Wedag, Cologne, Germany (1993).

Sutoh, K., M. Murata, S. Hashimoto, I. Hashimoto, S. Sawamura and H. Ueda, 1992. *Gegenwärtiger Stand der Vormahlung von Klinker und Zementrohmaterialien nach dem CKP-System*, ZKG 1 45 pp.21-25 (1992).

Suzuki, K., H. Tochinai, T. Uematsa, and S. Mishiro, 1993. "A New Grinding Method for Ceramics Uisng a Biaxially Vibrated Nonrotational Ultrasonic Tool" CIRP Annuals 1 42 pp.375-378 (1993).

Swaine, D.J. and F. Goodarzi (eds), *Environmental aspects of trace elements in coal*, Kluwer Academic Publishers, Dordrecht, The Netherlands, 1995

Swamy, R. N. (editor). 1991. *Blended Cements in Construction (Papers presented at the International Conference on Blended Cements in Construction, University of Sheffield, UK, September 9-12, 1991)*. London/New York: Elsevier Applied Science. 508 pp.

Tokheim, L.A., D. Bjerketvedt, I. Husum, and O. Hoidalen, 1998. *NO_x Minderung in einem Zementofen mit Vorcalcinierung durch Reduzierende Verbrennung von Kunststoffen*, ZKG International 1 51 pp.12-23 (January 1998).

Turkenburg, W.T.C., 1997. *Sustainable Development, Climate Change, and Carbon Dioxide Removal (CDR),* Energy Conservation and Management, vol.38 (suppl.) p.503-512.

Ullman, F., 1991. *The Japanese Cement Industry*, Rock Products April: 47-51.

Van der Vleuten, 1994, *Strategies and Instruments to promote Energy Efficiency in Developing Countries, Cement in development: energy and environment*, working paper no. 4, ECN, pp. 63-67

Van Kuijk, A.H.J., A.M. Schakel and P. Vissers, 1997. *Dutch Notes on BAT for the Production of Cement Clinker*, Ministry of Housing, Spatial Planning and the Environment, The Hague, The Netherlands.

Venkateswaran, S.R. and H.E. Lowitt, 1988. *The U.S. Cement Industry, An Energy Perspective*, U.S. Department of Energy, Washington D.C., USA.

Vleuten, F.P. van der, 1994. *Cement in Development: Energy and Environment*, Netherlands Energy Research Foundation, Petten, The Netherlands.

WEC, 1995. *Efficient Use of Energy Utilizing High Technology: An Assessment of Energy Use in Industry and Buildings,* World Energy Council, London, United Kingdom.

Worrell, E., J.W. Bode, J.G. de Beer, 1997. *Energy Efficient Technologies in Industry - Analysing Research and Technology Development Strategies - The 'Atlas' Project*, Dept. of Science, Technology & Society, Utrecht University, Utrecht, The Netherlands.

Worrell, E., R. Smit, D. Phylipsen, K. Blok, F. van der Vleuten and J. Jansen, 1995. *International Comparison of Energy Efficiency Improvement in the Cement Industry*, Proceedings ACEEE 1995 Summer Study on Energy Efficiency in Industry (Volume II).

ANNEX 1. OPTIONS TO IMPROVE ENERGY EFFICIENCY OF THE CEMENT PRODUCTION PROCESS

Process Control & Management Systems

Description:
Heat from the kiln may be lost through non-optimal process conditions or process management. Automated computer control systems may help to optimise the combustion process and conditions. Improved process control will also help to improve the product quality, e.g. reactivity and hardness of the produced clinker, which may lead to more efficient clinker grinding.
In cement plants across the world, different systems are used, marketed by different manufacturers. Most modern systems use so-called 'fuzzy logic'. Fuzzy logic systems do not use a modelled process to control process conditions, but try to simulate the best controller, using information from various stages in the process. 'Fuzzy logic' systems are also described as 'neural networks'. One such system, called LINKman, was originally developed in the United Kingdom by Blue Circle Industries and SIRA [ETSU, 1988]. The first system was installed at Blue Circle's Hope Works in 1985, which resulted in a fuel consumption reduction of nearly 8% [ETSU, 1988]. The LINKman system has successfully been used in both wet and dry kilns.

Application:
After their first application in 1985, 'fuzzy logic' systems now find wider application and can be found in many European plants, in countries such as The Netherlands, the U.K. and the U.S. However, we assume that improved process control systems can still be applied in many plants around the world.

Energy Savings:
Energy savings may vary between 2.5% and 10% [ETSU, 1988; Haspel and Henderson, 1993], and the typical savings are estimated at 2.5-5%. We estimate the savings at 0.1-0.3 GJ/tonne clinker. Power savings are small, and estimated at 7.5-10% [Haspel and Henderson, 1993], or 3-4 kWh/tonne clinker ground.

Emission Reduction:
Carbon emissions will be reduced through reduction of energy-related emissions. Energy-related emissions will typically be reduced by 2.5-5%.

Economics: The economics of advanced process control systems are very good and payback periods can be as short as 3 months [ETSU, 1988]. The system at Blue Circle's Hope Works needed an investment of £203,000 (1987), equivalent to 0.2 £/tonne clinker [ETSU, 1988], including measuring instruments, computer hardware and training.

Other Benefits:
Enhanced computer control may result in substantial other savings as well, through increased productivity (by 2.5-10%) and improved product quality, resulting in increased strength of the cement [Haspel and Henderson, 1993] and lower NO_x emissions through better control of combustion conditions [Van Kuijk, 1997].

Raw Meal Homogenising Systems

Description:
In order to be able to produce a good quality product and to maintain optimal and efficient processing conditions in the kiln, it is crucial that the raw meal is chemically uniform. Most plants use compressed air to agitate the powdered meal in so-called air-fluidised homogenising silos (using 1-1.5 kWh/tonne raw meal). Older dry process plants use mechanical systems, which simultaneously withdraw material from (6-8) different silos at variable rates [Fujimoto, 1993], using 2-2.6 kWh/tonne raw meal. Modern plants use gravity-type homogenising silos, saving power use. In these silos, material funnels down one of many discharge points, where it is mixed in an inverted cone. Gravity-type silos may not give the same blending efficiency as air-fluidised systems, which can be solved by installing on-line analysers for raw mix control [Fujimoto, 1993; Holderbank, 1993].

Application:
Although most older plants use mechanical or air-fluidised bed systems, more and more new plants seem to have gravity-type silos, because of the significant reduction in power consumption [Holderbank, 1993]. It is unlikely that silos will be replaced simply to improve energy efficiency. A new silo is, however, feasible when a new plant is built or when existing facilities are completely reconstructed.

Energy Savings:
The energy savings are estimated at 0.9 - 2.5 kWh/tonne raw meal [Fujimoto, 1993; Holderbank, 1993; Alsop & Post, 1995]. Consuming 1.5-1.6 tonnes of raw meal per tonne clinker results in a power saving of 1.4 - 4.0 kWh/tonne clinker.

Emission Reduction:
Implementing an efficient raw meal homogenising system does not lead to a direct reduction of emissions. Implementation will, however, reduce power needs and hence reduce emissions due to reduced power generation. The emission reduction will strongly depend on the mode and efficiency of power generation.

Economics:
No cost information was available for this study.

Other Benefits:
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Wet Process Conversion to Semi-Wet Process Kiln

Description:
In the semi-wet process, the water content of the raw meal is reduced by a slurry filter press in order to reduce the moisture content and to obtain a paste ready for extrusion to pellets or filer cake. The pellets are fed to the kiln. The filter press reduces the moisture content to a 14-22% level [Holderbank, 1993; Vleuten, 1994]. The semi-wet process was developed in the early 1960s as a possible improvement on the standard long wet kiln.

Application:
The semi-wet process is mainly adopted by existing wet process plants as a process modification. The age and expected lifetime of the kiln determine whether or not the filter press can be implemented.

Energy Savings:
The semi-wet process leads to an estimated fuel saving of 0.8-1.6 GJ/tonne clinker due to the reduced energy needs to evaporate the water [CowiConsult, 1993]. The filter press leads to an increased electricity use of 3 to 5 kWh/tonne clinker [CowiConsult, 1993].

Emission Reduction:
The process modification leads to a similar reduction level of all energy-related emissions. The literature reports no net effect of the modification on the specific NO_x or SO_2 emissions.

Economics:
The reduced fuel costs are partially offset by the costs for increased power consumption and the costs for the maintenance and replacement of the filter cloth. No specific cost data were found in the literature.

Other Benefits:

Wet Process Conversion to Dry Process Kiln

Description:
The conversion from an existing wet kiln process to a preheater dry kiln process is economically feasible under specific conditions. The reconstruction involved is very complex, and may affect almost all parts of the existing plant. As described above, a dry process kiln is far more energy-efficient than a wet kiln. The actual efficiency will depend on the humidity of the limestone reserves used. Wet kilns may be old plants or plants originally operating in areas with an unreliable power supply or areas with very humid limestone reserves. Wet plants are primarily found in Eastern Europe, in some developing countries and in some OECD countries (UK, US).

Application:
Reconstructing existing wet plants may only be economically attractive in regions with growing markets, or with high or growing energy prices. Especially in Eastern Europe conversion could be an attractive option to make existing facilities competitive.

Energy Savings:
Energy savings will strongly depend on the efficiency of the existing facility, limestone moisture content and the new process installed. Fuel savings are estimated at roughly 2.2 GJ/tonne and power use may increase by about 10 kWh/tonne clinker [Vleuten, 1994] when replacing a wet kiln by a multi-stage preheater and precalciner kiln. This will result in a fuel use between 3.13 and 3.25 GJ/tonne clinker [Anonymous, 1994; Vleuten, 1994]

Emission Reduction:
The NO_x emissions may be reduced, although the extent will strongly depend on the fuels used previously in the wet kiln and the firing process in the new dry kiln.

Economics:
The cost of converting a wet plant to a dry process plant may be high, as it basically involves the full reconstruction of an existing facility. Vleuten [1994] quotes an estimated cost of 133 US$/tonne annual capacity. Costs may vary in accordance with variations in labour costs across the world. The main equipment manufacturers are, however, found in Western Europe, Japan and the U.S.

Other Benefits:
The conversion to a dry process kiln will result in a much higher production capacity.

Dry Process Conversion to Multi-Stage Preheater Kiln

Description:
Older dry kilns do not have preheaters, but only one-, two- or three-stage preheating. This leads to higher heat losses. Hence, installing multi-stage suspension preheating (i.e. four- or five-stage) may reduce the heat losses and thus increase efficiency. Modern cyclone or suspension preheaters also have a reduced pressure drop, leading to increased heat recovery efficiency and reduced power use in fans. Four-stage preheating became the standard technology in the 1970s. As the lifetime of a kiln often exceeds 30-40 years, many dry process plants can be found around the world, which do not have four-stage preheating. By installing new preheaters, the productivity of the kiln will also increase, due to a higher degree of pre-calcination (up to 30-40%) as the feed enters the kiln. As the capacity increases, the clinker cooler may also have to be adapted in order to be able to cool the large amounts of clinker.

Application:
The conversion of older kilns is attractive when the old kiln needs replacement and a new kiln would be too expensive. Conversion is, however, not economically feasible for energy efficiency reasons alone. Older dry kilns can be found all over the world, i.e. dry process kilns that are 25 years old or over and that have not been reconstructed since.

Energy Savings:
Energy savings depend strongly on the specific energy consumption of the dry process kiln to be converted as well as the number of preheaters to be installed. For example, a cement kiln in the former German Democratic Republic was rebuilt by Lafarge to replace four dry process kilns originally constructed in 1973 and 1974. In 1993 and 1995 three kilns were equipped with four-stage suspension preheaters. The specific fuel consumption was reduced from 3.9 GJ/tonne to 3.4 GJ/tonne clinker, while the capacity of the individual kilns was increased from 1500 to 2300 tpd [Duplouy and Trautwein, 1997]. In the same project, the power consumption was reduced by 25%, due to the replacement of fans and the finish-grinding mill.

Emission Reduction:
The NO_x emissions are reduced to the same degree as the energy consumption, as are the CO_2 emissions. Dust emissions were also reduced in the German project due to the installation of new dust filters [Duplouy and Trautwein, 1997].

Economics:
A Canadian study estimates the specific costs at 30-40 US$/tonne capacity for conversion to a multi-stage preheater kiln [Holderbank, 1993]. The total project costs for the East German plant were 350 Million DM, equivalent to approximately 170 DM/year or 95 US$/year [Duplouy and Trautwein, 1997]. In this cost estimate, the conversion costs are overestimated, as the project included the installation of new dust filters, a finish grinding mill and changes in the air supply system and clinker storage.

Other Benefits:

Increasing the number of preheater stages may increase the clinker production capacity. The reconstruction of WerkKarsdorf in the former German Democratic Republic led to an increased production capacity of 53% [Duplouy and Trautwein, 1997].

Dry Process Conversion to Preheater-Precalciner Kiln

Description:
An existing preheater kiln may be converted to a multi-stage preheater precalciner kiln by adding a precalciner and, when possible and necessary, an extra preheater. The addition of a precalciner will generally increase the capacity of the plant, while lowering the specific fuel consumption. Using as many features of the existing plant and infrastructure as possible, special precalciners have been developed by various manufacturers to convert existing plants, e.g. Pyroclon®-RP by KHD in Germany. Generally, the kiln, foundation and towers are used in the new plant, while cooler and preheaters may be replaced. Cooler replacement may be necessary in order to increase the cooling capacity for larger production volumes. The recent conversion of a plant in Italy, using the existing rotary kiln, lead to a capacity increase of 80-100% (from 1000 tpd to 1800-2000 tpd), while reducing energy use from 3.56 to 3.06-3.19 GJ/tonne clinker, resulting in a saving of 11-14% [Sauli, 1993].

Application:
Converting an existing plant is not commercially attractive for energy efficiency reasons alone. Conversion is attractive only when an existing facility needs to be modernised for other reasons and when capacity expansion is attractive.

Energy Savings:
Fuel savings will depend strongly on the efficiency of the existing kiln and on the new process parameters (e.g. degree of precalcination, efficiency cooler). Based on the experiences with the Italian plant, we estimate the savings at roughly 12%, or 0.44 GJ/tonne clinker [Sauli, 1993].

Emission Reduction:
NO_x emission reduction will be concurrent with the energy savings. However, the reduction may be higher due to the combustion of some fuel at lower temperatures in the precalciner. Also, the precalciner allows the use of more alternative fuels.

Economics:
Sauli [1993] does not outline the investments made for the conversion project. Vleuten [1994] estimates the cost of adding a precalciner or suspension preheaters at 28 US$/tonne annual capacity. It is not clear what is included in this estimate, nor is it clear to which region this figure applies. Energy savings and the possibility to use a larger amount of alternative fuels may result in lower operating costs.

Other Benefits:
The major other benefits are the capacity increase, the opportunity to increase the use of alternative (cheaper) fuels, as well as the possibility to reduce NO_x emissions [Conroy, 1997].

Cooler Conversion to Grate Cooler

Description:
Four main types of coolers are used in the cooling of clinker: shaft, rotary, planetary and grate cooler. No shaft coolers are in use anymore. The grate cooler is the modern variant and is used in almost all modern kilns. The advantages of the grate cooler are its large capacity (allowing large kiln capacities) and efficient heat recovery (the clinker leaves the cooler at 83 ºC, instead of 120-200 ºC [Vleuten, 1994]). Modern grate coolers recover more heat than do the other types of coolers. For large capacity plants, grate coolers are the preferred equipment. For smaller plants the grate cooler may be too expensive [CowiConsult, 1992]. Grate coolers are essential if a precalciner is installed, as the grate preheater produces the required tertiary air. Replacement of planetary coolers by grate coolers is not uncommon [Alsop and Post, 1995]

Application:
Grate coolers are standard technology for modern large-scale kilns. Planetary and rotary coolers are found in older kilns (built between 1970 and 1980) only. In the EU-12 (1990) less than 30% of the clinker capacity had planetary coolers [CowiConsult, 1990]. Depending on the age of the plants, this percentage may be higher in other regions.

Energy Savings:
When compared to a planetary cooler, an additional heat recovery of up to 0.1-0.3 GJ/tonne clinker is possible with grate coolers, at an extra power consumption of approximately 3 kWh/tonne clinker [CowiConsult, 1992; Vleuten, 1994]. The savings are estimated to be up to 8% of the fuel consumption in the kiln [Vleuten, 1994].

Emission Reduction:
Emission reduction of energy-related emissions is roughly equal to that of the reduction in energy use. The excess air used in the grate cooler makes the use of dedusting equipment necessary [Vleuten, 1994]. The lower clinker temperature at the exit of the cooler leads to less thermal losses.

Economics:
No cost information is available for this study. Cooler conversion probably is economically attractive only when installing a precalciner, which is necessary to produce the tertiary air (see above).

Other Benefits:
The larger throughput allows a capacity increase in existing kilns and is necessary when a precalciner is installed. The lower exit temperature of the clinker allows direct processing in the finish grinding line.

LEPOL Kilns: Improved Preheating

Description:
In LEPOL kilns the raw meal (containing 10-12% water) is preheated in a two chambers travelling grate preheater, leading to energy savings when compared to the traditional wet process. In the grate preheater, the material is pre-calcined (to approximately 25-30%). Improved heat recovery could increase the precalcination range and hence the kiln capacity. However, improved preheating is hindered by high alkali and dust concentrations, reducing permeability and hence heat transfer.

Within the European THERMIE programme, an improved preheating circuit was designed and demonstrated at Cimenteria di Morano, Italy [Crossila and Häutle, 1997]. Although the available data are based on limited test results, the system did lead to energy savings and improved production capacity.

Application:
The improved hot gas circuit for the preheater in a LEPOL kiln is a recent development and implementation is expected to be very limited. The process can be applied in LEPOL kilns only. LEPOL kilns can be found in e.g. France, Germany, Italy and many other places.

Energy Savings:
Fuel savings after installing the new hot gas circuit are estimated at 220 MJ/tonne clinker, or 6.3% to 3.3 GJ/tonne clinker [Crossila and Häutle, 1997]. LEPOL kilns may use as much as 3.5-3.6 GJ/tonne clinker [CowiConsult, 1992]. Due to the increased output, power use for driving the kiln and fans is also reduced, although only by 0.2 kWh/tonne, or 1% [Crossila and Häutle, 1997].

Emission Reduction:
The CO_2 emission is reduced by 6% of the fuel emissions, or about 2-3% of the total emissions for the production of one tonne clinker.

Economics:
No investment data are available, although the payback period is reported to be satisfactory [Crossila and Häutle, 1997].

Other Benefits:
The main advantage is the increased process output (+14%) of the kiln, as the result of granules bed permeability improvement. The energy savings will result in an equivalent reduction of the NO_x and SO_2 emissions.

Optimisation of Heat Recovery in the Clinker Cooler (dry process)

Description:
The clinker cooler cools clinker from 1200 ºC down to 100 ºC . The most common cooler designs are of the rotary, planetary (or satellite) and grate type. All coolers heat the secondary air for the kiln combustion process and sometimes also tertiary air for the precalciner [Alsop and Post, 1995]. Grate coolers are the modern variant and are suitable for large-scale kilns (up to 10,000 tpd). Grate coolers use electric fans and excess air. Rotary coolers (used for approximately 5% of the world clinker capacity for plants up to 2000-4500 tpd) and planetary coolers (used for 10% of the world capacity for plants up to 3000-4000 tpd) do not need cooler fans and use little excess air, resulting in relatively lower heat losses [Buzzi and Sassone, 1993; Vleuten, 1994]. Improving heat recovery efficiency in the cooler results in fuel savings, but may also influence product quality and emission levels. Heat recovery can be improved through reduction of excess air volume [Alsop and Post, 1995], control of clinker bed depth and new grates [Buzzi and Sassone, 1993]. Control of cooling air distribution over the grate may result in lower clinker temperatures and high air temperatures.

Application:
Improved grate coolers can be used in 100% of the global clinker capacity and can be applied to rebuild existing plants [Buzzi and Sassone, 1993]. In the EU-12, over 70% of the clinker coolers were grate coolers, the rest being mainly planetary coolers [CowiConsult, 1992]

Energy Savings:
Additional heat recovery results in reduced energy use in the kiln and precalciner, due to higher combustion air temperatures. The fuel savings are estimated at up to 0.48 GJ/tonne clinker in the U.S. [WEC, 1995]. In India, small improvements in the clinker cooler were estimated to save at least 0.21 GJ/tonne clinker [Mall and Varshney, 1992].

Emission Reduction:
Note that higher combustion air temperatures may result in higher specific NO_x emission levels. However, low NO_x burners (with a 30% reduction in NO_x emission [Holderbank, 1993]) and increased use of pre-calcination will result in lower specific NO_x emission levels. Hence, improved clinker coolers may not have a net effect on NO_x emissions. Dust emissions may be reduced due to improved control of the cooling process.

Economics:
No specific cost information is available for this study.

Other Benefits:
Optimising clinker coolers may result in an increased capacity of the kiln, due to lower waste heat losses and higher combustion air temperatures. Optimised clinker cooling may also result in reduced maintenance of the grate [Buzzi and Sassone, 1993].

High-Efficiency Motors and Drives

Description:
Motors and drives are used throughout the cement plant to drive fans (preheater, cooler, alkali bypass), rotate the kiln, transport materials and, most importantly, for grinding. In a typical cement plant 500-700 electric motors may be used, varying from a few kW to MW-size [Vleuten, 1994]. Efficient clinker grinding is discussed below. Variable speed drives, improved control strategies and high-efficiency motors can help to reduce power use in cement kilns.

Application:
If the replacement does not influence the process operation, motors may be replaced at any time. However, motors are often rewired rather than being replaced by new motors.

Energy Savings:
Power savings may vary considerably on a plant-by-plant basis, ranging from 3 to 8% [Fujimoto, 1993]. Vleuten [1994] estimates the potential power savings at 8% of the power use.

Emission Reduction:
The use of high-efficiency electric motors does not lead to a direct reduction of emissions. Implementation will reduce power needs and hence reduce emissions due to reduced power generation. The emission reduction will strongly depend on the mode and efficiency of the power generation.

Economics:
High-efficiency motors cost approximately the same as, or only a little bit more than, regular motors.

Other Benefits:

Adjustable Speed Drives

Description:
Drives are the largest power consumers in cement making. The energy efficiency of a drive system can be improved by reducing the energy losses or by increasing the efficiency of the motor (see above). Energy losses in the system can be diminished by reducing throttling and coupling losses can be reduced through the installation of adjustable speed drives (ASD). Most motors are fixed speed AC models. However, motor systems are often operated at partial or variable load [Nadel, 1992]. Also, in cement plants large variations in load occur [Bösche, 1993]. There are various technologies to control the motor [Worrell, 1997]. The systems are offered by many suppliers and are available worldwide. Worrell *et al*. [1997] provide an overview of savings achieved with ASD in a wide array of applications. The savings depend on the flow pattern and loads. Generally, the savings vary between 7 and 60%.

Application:
ASD equipment is used more and more in cement plants [Bösche, 1993; Fujimoto, 1993], but the application may vary widely, depending on electricity costs. Within a plant, ASDs can mainly be applied for fans in the kiln, cooler, preheater, separator and mills, and for various drives. One case study for a modern cement plant estimated potential application for 44% of the installed motor power capacity in the plant [Bösche, 1993].

Energy Savings:
Energy savings strongly depend on the application and flow pattern of the system on which the ASD is installed. Although savings are significant [Holderbank, 1993], not many quantitative studies are available for the cement industry. One hypothetical case study estimates the savings at 70%, compared to a system with a throttle valve (or 37% compared with a regulated system) for the raw mill fan [Bösche, 1993]. We will estimate the potential savings at 20% for 44% of the installed power, or roughly equivalent to 10 kWh/tonne cement.

Emission Reduction:
The use of ASDs does not lead to a direct reduction of emissions. Implementation will reduce power needs and hence reduce emissions due to reduced power generation. The emission reduction will strongly depend on the mode and efficiency of power generation.

Economics:
The specific costs depend strongly on the size of the system. For systems over 300 kW the costs are estimated at 70 ECU/kW (75 US$/kW) or less and for the range of 30-300 kW at 115-130 ECU/kW (120-140 US$/kW) [Worrell, 1997]. Using these cost estimates, the specific costs for a modern cement plant, as studied by Bösche [1993], the costs can be estimated at roughly 0.9-1.0 US$/tonne cement.

Other Benefits:
The use of ASDs may reduce wear and strain on the system due to surge-free starting and reduced speeds. It may also substantially reduce the noise volume [Bösche, 1993].

Efficient Grinding Technologies

Description:
Electricity use for raw meal and finish grinding depends strongly on the hardness of the material (limestone, clinker) and the desired fineness of the cement as well as the amount of additives. Blast furnace slags are harder to grind and hence use more grinding power. To be able to compare mill efficiencies, the produced cement should have similar properties. Traditionally, ball or tube mills are used in finish grinding, while many plants use vertical roller mills for raw meal grinding. Modern state-of-the-art concepts are the high-pressure roller mill and the horizontal roller mill [Seebach, 1996]. Ball mills may use between 32 and 37 kWh/tonne [Seebach, 1996] for cements with a Blaine of 2950-3200 cm^2/g.

New mill concepts may reduce the power consumption by 28-38% to 22-27 kWh/tonne clinker for systems including a high-pressure rolling mill and a ball mill, or 44-55% for concepts using only a high-pressure rolling mill [Seebach, 1996]. Today, high-pressure rolling mills are most often used to expand the capacity of existing grinding mills. In a high-pressure rolling mill, two rollers put the material under a pressure of up to 3500 bar [Buzzi, 1997], improving the grinding efficiency dramatically [Seebach, 1996].

The horizontal roller mill is a new concept, first demonstrated in Italy in 1993, which can be used to produce finished product as well as for grinding coal and raw material [Buzzi, 1997]. A horizontal roller, within a cylinder, is driven. The centrifugal forces resulting from the movement of the cylinder cause a uniformly distributed layer to be carried on the inside of the cylinder. The layer passes the roller (with a pressure of 500-1000 bar). The finished product is collected in a dust filter. The Horomill is a compact mill that can produce a finished product in one step and hence has relatively low capital costs. Grinding Portland cement with a Blaine of 3200 cm^2/g consumes approximately 23 kWh/tonne [Buzzi, 1997] and even for Pozzolanic cement with a Blaine of 4000 c m^2/g power use may be as low as 28 kWh/tonne (equivalent to a saving of approximately 40% compared to a conventional ball mill) [Buzzi, 1997].

Application:
High-pressure roller mills can be found in modern grinding facilities around the world, but especially in countries with high electricity costs such as Japan, South Korea and Western European countries, or countries with poor power supply such as India and Argentina [Seebach, 1996]. After the first demonstration of the horizontal roller mill in Italy, this concept is now also applied in plants in Mexico [Buzzi, 1997] and Germany [Duplouy and Trautwein, 1997].

Energy Savings:
Assuming a power consumption of 38 kWh/tonne for cement with a Blaine of 3200 cm^2/g for a ball mill, the electricity savings of new finish grinding mill concepts is estimated at 16-19 kWh/tonne (or 40-50%).

Emission Reduction:
No direct reduction of emissions.

Economics:
Capital cost estimates for installing a new roller press vary widely in the literature, ranging from low estimates like 2.5 [Holderbank, 1993] or 3.6 US$/tonne [Kreisberg, 1993] to high estimates of 8 US$/tonne capacity [CowiConsult, 1992]. We estimate the costs at approximately 4 US$/tonne capacity. The capital costs of roller press systems are lower than those for other systems [Kreisberg, 1993] or at least comparable [Patzelt, 1993]. Some new mill concepts may lead to a reduction in operation costs of as much as 30-40% [Sutoh, 1992].

Other Benefits:
The new mill concepts result in a higher productivity of finish grinding compared to conventional ball mills (up to 20% more throughput) as well as improved product quality (due to a more uniform size distribution) [Buzzi, 1997; Seebach, 1996]. Currently, the new mills are used for the capacity expansion of existing plants or for greenfield plants only.

High-efficiency Classifiers

Description:
A recent development is high-efficiency classifiers or separators. Classifiers separate the finely ground particles from the coarse particles. The large particles are then recycled back to the mill. Standard classifiers may have a low separation efficiency, which leads to the recycling of fine particles, leading to extra power use in the grinding mill. Various concepts of high-efficiency classifiers have been developed [Holderbank, 1993; Süssegger, 1993]. In high-efficiency classifiers, the material stays longer in the separator, leading to sharper separation, thus reducing overgrinding.

Application:
High-efficiency separators may be used, especially in areas with high electricity costs. The use of high-efficiency separators in the EU-12 [1990] was estimated at 35% in finish grinding [CowiConsult, 1992]. No data are available about the use of high-efficiency classifiers for other countries.

Energy Savings:
Electricity savings through implementing high-efficiency classifiers are estimated at 8% of the specific electricity use [Holderbank, 1993]. Various case studies have shown a reduction of 1.7-2.3 kWh/tonne cement [Salzborn and Chin-Fatt, 1993; Süssegger, 1993]. Efficient classification of the cement (improved size distribution) may make it possible to produce a cement with a similar strength at a lower fineness, increasing energy savings.

Emission Reduction:
The use of high-efficiency classifiers does not lead to a direct reduction of emissions. Implementation will reduce power needs and hence reduce emissions due to reduced power generation. The emission reduction will strongly depend on the mode and efficiency of power generation.

Economics:
The costs of a high-efficiency classifier (including auxiliaries) are estimated at 2.5-3 US$/tonne cement [Holderbank, 1993].

Other Benefits:
Replacing a conventional classifier by a high-efficiency classifier has led to 15% increases in the grinding mill capacity [Holderbank, 1993] and improved product quality due to a more uniform particle size [Salzborn and Chin-Fatt, 1993], both in raw meal and cement.

Shaft Kilns: Efficient Kiln Technology (China)

Description:
In China, India and other developing countries large numbers of shaft kilns can be found. Shaft kilns are less capital-intensive and are more suitable for regions, which do not have a very good infrastructure (the transportation of raw materials and products, and power production). Fuel intensities of shaft kilns vary widely. For example, in China the average fuel intensity is estimated at 4.8 GJ/tonne, varying between 3.2 and 6.6 GJ/tonne clinker [Feng, 1995]. In China a wide number of energy saving measures have been developed to improve the efficiency of existing kilns. Shaft kilns have been renovated to improve control of the raw material input and pellet production, optimise the kiln size and shape, improve insulation and to computer-control operation of the kiln. These measures result in a 10-30% saving on fuel use.

Application:
These measures are suitable for shaft kilns only. The described measures were implemented in Chinese shaft kilns. In China, 71% (1990) of clinker was produced using 5700 shaft kilns, or 149 Mtonnes [Feng, 1995].

Energy Savings:
Fuel savings are estimated at 10-30%, or 1.2 GJ/tonne for the 1990 mix of manually and mechanically operated kilns [Feng, 1995].

Emission Reduction:
The suggested technologies to renovate shaft kilns do not specifically reduce the NO_x or SO_2 emissions. Emission reduction is equal to the reduction in energy use, or 25% of the 1990 emission average.

Economics:
The investment costs for the renovation of Chinese shaft kilns is estimated at 230 Yuan per tonne capacity (1990) [Feng, 1995]. Renovation will also result in an increased production capacity. Under 1990 economic conditions the investment could have a payback period of less than 2 years.

Other Benefits:
The suggested changes in technology result in substantial increases in the production capacity. As the technology is made in China, no (expensive) technology import is needed.

Fluidised Bed Kiln

Description:
Developments in FBK technology started as early as the 1950s [Venkateswaran, 1988]. Today, developments mainly take place in Japan (Kawasaki Heavy Industries) and the U.S. (Fuller Co.) [Cohen, 1995; Van Kuijk, 1997]. In an FBK, the rotary kiln is replaced by a stationary kiln, in which the raw materials are calcined in a fluidised bed. An overflow at the top of the reactor regulates the transfer of clinker to the cooling zone. The (expected) advantages of FBK technology are lower capital costs because of smaller equipment, lower temperatures resulting in lower NO_x -emissions and a wider variety of the fuels which can be used, as well as lower energy use. The Kawasaki design uses cyclone preheaters, a precalciner kiln and a fluidised bed kiln. The Fuller Co. is the main developer in the US of a fluidised bed kiln for clinker making. Early developments did not prove to be commercially successful due to the high clinker recycling rate [Cohen, 1992] and were commercialised for alkali dust recycling only [Cohen, 1993]. The technology was also used in the development of the advanced cement furnace (CAF). CAF uses a preheated pellet feed, using primarily natural gas or liquid fuels [Cohen, 1993]. A pilot plant was built and used to produce clinker. The NO_x emissions were reduced to 0.86 kg/tonne clinker, compared to 2.3-2.9 kg/tonne for conventional plants [Cohen, 1993]. The future fuel consumption is estimated at 2.93-3.35 GJ/tonne clinker [Cohen, 1995].

Application:
The fluidised bed kiln is a completely new kiln design and would only be suitable for new plants with a capacity of up to 360,000 tonnes per year [Cohen, 1993]. As the technology is still under development, commercial implementation is not expected in the next decade.

Energy Savings:
The fuel use of the FBK may be comparable to or lower than that of conventional rotary kilns, although modern precalciner rotary kilns have shown fuel use of 2.9-3.0 GJ/tonne clinker. Cohen [1995] expects a future fuel use of 2.93-3.35 GJ/tonne clinker. No data are available on the expected power use for the FBK, but may be high.

Emission Reduction:
FBK may result in relatively low NO_x emissions (estimated at 0.86 kg/tonne clinker) [Cohen, 1993] due to lower combustion temperatures. Japanese test results have shown a 20% reduction in NO_x emissions for fuel oil and a 60% reduction for pulverised coal [Van Kuijk, 1997]. The use of natural gas in FBK technology will also result in lower SO_2 emissions. Note that the CO_2 emission reduction due to the use of natural gas is added to the emission reduction due to fuel savings. With similar fuel consumption, the use of natural gas may result in a CO_2 emission reduction of 40% in comparison with coal fuelling.

Economics:
As there are no commercial plants, it is difficult to estimate the investment costs. Smaller equipment may, however, result in lower investment costs [Cohen, 1992].

Also, the reduction of the number of moving parts will result in lower maintenance costs [Cohen, 1992].

Other Benefits:
The use of FBK may result in lower alkali-content of the clinker [Cohen, 1992]. FBK needs less space and also has a higher flexibility when compared to raw material feed.

Advanced Comminution Technologies

Description:
Grinding is an important power consumer in modern cement making. However, current grinding technologies are highly inefficient. Over 95% of the energy input in the grinding process is lost as waste heat, while only 1-5% of the energy input is used to create new surface area [Venkateswaran and Lowitt, 1988]. Some of the heat may be used to dry the raw materials, for example in finish grinding or the grinding of limestone or slag. Current high-pressure processes already improve the grinding efficiency in comparison with conventional ball mills (see above). In the longer term further efficiency improvements can be expected when non-mechanical "milling" technologies become available [OTA, 1993]. Non-mechanical systems may be based on ultrasound [Suzuki, 1993], laser, thermal shock, electric shock or cryogenics. However, non-mechanical grinding technologies have not been demonstrated yet and will not be commercially available in the next decades.

Application:
Research and development into advanced processes is still going on. Hence, no applications can be defined as yet.

Energy Savings:
Although the theoretical savings of non-mechanical comminution are large, no estimate of the expected savings can be given at this stage of fundamental research.

Emission Reduction:
Non-mechanical comminution will reduce the energy-related emissions and may result in reduced dust emissions, as comminution may take place in a closed process.

Economics:
There is no information available on the economics.

Other Benefits:
No information available.

ANNEX 2. EUROPEAN CEMENT STANDARD

Table 6.1. The 27 products in the family of common cements [Source, Cembureau].

Main types	Notation of the 27 products (types of common cement)		Composition (proposition by mass[1])										
			Main constituents										Minor additional constituents
			Clinker	Blast Furnace slag	Silica fume[2]	Pozzolona		Fly ash		Burnt shale	Limestone		
						natural	natural calcined	siliceous	calcareous				
			K	S	D	P	Q	V	W	T	L	LL	
CEM I	Portland	CEM I	95-100										0-5
CEM II	Portland-slag	CEM II/A-S	80-94	6-20									0-5
		CEM II/B-S	65-79	21-35									0-5
	Portland –silica fume	CEM II/A-D	90-94		6-10								0-5
	Portland-pozzolana	CEM II/A-P	80-94			6-20							0-5
		CEM II/B-P	65-79			21-35							0-5
		CEM II/A-Q	80-94				6-20						0-5
		CEM II/B-Q	65-79				21-35						0-5
	Portland fly-ash	CEM II/A-V	80-94					6-20					0-5
		CEM II/B-V	65-79					21-35					0-5
		CEM II/A-W	80-94						6-20				0-5
		CEM II/B-W	65-79						21-35				0-5
	Portland burnt shale	CEM II/A-T	80-94							6-20			0-5
		CEM II/B-T	65-79							21-35			0-5
	Portland-limestone	CEM II/A-L	80-94								6-20		0-5
		CEM II/B-L	65-79								21-35		0-5
		CEM II/A-LL	80-94									6-20	0-5
		CEM II/B-LL	65-79									21-35	0-5
	Portland-composite[3]	CEM II/A-M	80-94	6-20									0-5
		CEM II/B-M	65-79	21-35									0-5
CEM III	Blastfurnace	CEM III/A	35-64	36-65									0-5
		CEM III/B	20-34	66-80									0-5
		CEM III/C	5-19	81-95									0-5
CEM IV	Pozzolanic[3]	CEM IV/A	65-89		11-35								0-5
		CEM IV/B	45-64		36-55								0-5
CEM V	Composite[3]	CEM V/A	40-64	18-30		18-30							0-5
		CEM V/B	20-38	31-50		31-50							0-5

1. The values of the table refer to the sum of the main and minor additional constituents.
2. The proportion of silica fume is limited to 10%
3. In Portland-composite cements II/A-M and CEM/B-M, in Pozzolanic cements CEM IV/A and CEM IV/B and in Composite cements CEM V/A and CEM V/B the main constituents besides clinker shall be declared by designation of the cement.

ANNEX 3. LEGISLATION ON EMISSIONS IN THE EU

Table 6.2 Summary of existing legislation in various European countries on emission limits for cement plants using conventional fuels and raw materials.

	Austria		Switzerland		Germany		France		Denmark	Netherlands
Dust	50		50		50		30 50 100		100	50
NO_x (as NO_2)	500 1000	1 2	800		1300- 1500 1800 800/500		1200 1500 1800		500	1500
SO_2	200 400		500		400		500 1200 1800		500	400
CO	-		-		-		-		-	
F^-	-		5		5		5		5	5
Cl/Cl^-	-		5/30		5/30		-/40		5/100	5/30
Sb	-		5		5				5	
As	-		1		1				1	
Be	0.1		0.1		-		-		0.1	0.1
Pb			5		5				1	
Cd	0.1		0.2		0.2					
Cr	-		5		5				5	
Co			1		1				1	
Cu	-		5		5				5	
Mn	-		5		5				5	
Ni			1		1					
Hg	-		0.2		0.2				0.1	
Se	-		1		1				1	
Te	-		1		1				1	
Tl	0.1		0.2		0.2				0.1	
V	-		5		5				5	
Sn	-		5		5				5	
As, Co, Ni, Pb	1.0		-		-		-		1	-
Cd, Tl, Hg	-		0.2		0.2		0.2		0.1	0.2
As, Co, Ni, Se, Te	-		1		1		1			1
Sb, Cr, Cu, Mn, Sn, Pb	-		5		5		5		5	5
Emission limit as	HHV		HV		HHV		HV		HV	HV
related O_2 (vol-%)	10.0		not given		10.0		10.0		10.0	10.0
National regulation	BGBl. Nr. 63/1993 29.01.93		LRV 814.318.142 01.01.93		TA-Luft (1986f.)		ENV P 9320 03.05.93		EPA (358/91) 06.06.91	NLRV (90/2)

Table 6.3. Emission standards and process data for (co-) combustion processes. The table compares EU directive for hazardous and municipal waste incinerators; Cement BATNEEC (UK); EU directive applied for co-combustion (estimation at 40% substitution), and emission process data of waste incinerating and cement production [DGXII, 1996]

mg/Nm^{3}dry	Hazardous wastes incineration (11% O_2)	Municipal waste incineration (11% O_2)	Cement BATNEEC (6% O_2)	dir. 94/67 40% substitution. (6% O_2)	Cement (6% O_2)	Waste incinerator (11% O_2)
dust	10	30	50	40	16	5
SO_2	50	300	400	330	180	30
NO_x			800	800	800	60
CO	50	300	500	500	200	100
H2S			5	5	0.4	ND
HCl	10	50	30	10	7.5	20
HF	1	2	5	1	0.2	1
VOC	10	30	10	120	4	13
D/F (ng)	0.1	.01	0.1	0.1	0.03	.011
HM Class 1	0.1	.02	0.2	0.1	0.02	0.04
MH Class 2		1	1		0.01	0.05
HM Class 3	0.5	5	5	0.5	0.03	0.16

ANNEX 4. BASIC DATA ON ENERGY CONTENT AND CARBON DIOXIDE DEMISSION OF VARIOUS FUELS

Table 6.4. Energy content for various primary and alternative fuels.[1]

Fuel	Energy content (MJ/kg)	Fuel	Energy content (MJ/kg)
Primary energy carriers		**Alternative energy carriers**	
Coal	32	Scrap tyres	21
Fuel oil	40	Plastics	33
Natural gas	36	Waste oil	38
Petroleum coke	34	Paper residues	6
		Waste solvents	18-23

1. The average calorific value of fuels needed for clinkerisation is about 15 MJ/kg. The minimum calorific value to self-support the flame is 10 MJ/kg.

Table 6.5. Carbon dioxide emission factors for various primary and alternative fuels

Fuel	CO_2 emission factor (kg/MJ)	Fuel	CO_2 emission factor (kg/MJ)
Primary energy carriers		**Alternative energy carriers**	
Coal	0.103	Scrap tyres	-
Fuel oil	0.077	Plastics	-
Natural gas	0.056	Waste oil	-
Petroleum coke	0.073/0.095	Paper residues	-
		Waste solvents	-