CO$_2$ abatement in the cement industry

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Abstract

World cement production has been increasing steadily in the past and due to the unique nature of cement manufacturing, cement production is energy- and carbon-intensive. This makes it a key source of CO$_2$ emissions. Cement production accounts for around 7% of total industrial fuel use, and almost 25% of total direct CO$_2$ emissions from industry. It was estimated that in 2000, the cement industry emitted around 1.4 GtCO$_2$, which accounted for approximately 5% of the global total anthropogenic CO$_2$ emissions. This increased to 1.9 Gt in 2005, which was almost 8% of total global CO$_2$ emissions. This report reviews the current state of the cement industry in terms of CO$_2$ emissions and possible mitigation strategies. Technologies and other measures that improve the energy efficiencies and reduce CO$_2$ emissions in the cement production processes are examined. The costs of implementing the technologies and the resultant CO$_2$ savings are evaluated.

Abbreviations

ASU	air separation unit
CAP	chilled ammonia process
CCE	capital cost effectiveness
CDM	Clean Development Mechanism
CER	certified emission reduction
CSI	Cement Sustainability Initiative
EC	European Economic Community
EJ	exajoule = 10^{18} joules
FGD	flue gas desulphurisation
GDP	gross domestic production
GGBFS	ground granulated blast furnace slag
GHG	greenhouse gases
GJ	gigajoule = 10^9 joules
GNR	Getting the Number Right
Gt	billion metric tonnes
IEA	The International Energy Agency
kg	kilogramme
kWh	kilowatt hour
MPa	mega pascal
Mt	million tonnes
OPC	Ordinary Portland Cement
PJ	petajoule = 10^{15} joules
ppmv	parts per million by volume
R&D	research and development
SNCR	selective non-catalytic reduction
t/d	tonnes per day
TWh	terawatt hour
UNFCCC	United Nations Framework Convention on Climate Change
US EPA	US Environmental Protection Agency
VRM	vertical roller mill
WBCSD	World Business Council for Sustainable Development
WWF	The World Wildlife Fund

Contents

1   Introduction

Cement is the key ingredient in the production of concrete, which is the essential construction material for building houses, bridges, roads, dams and many other infrastructures. The continued global economic growth has resulted in an increasing demand for and production of cement over the last several decades. Production of cement consumes a significant amount of natural resources and energy, and the cement industry is a key source of CO_2 emissions.

World cement production has been increasing steadily over many decades and the increase has accelerated since 2000. The vast majority of the growth occurred in developing countries, especially China. Global total cement output increased by more than 283% between 1970 and 2005, and by 44.4% between 2000 and 2005 (Taylor, 2006; WWF, 2008; USGS, 2010). In 2008, a total of 2.8 billion tonnes (Gt) of cement was produced worldwide. In the same year, China alone produced 1.39 Gt of cement, almost 50% of the global total (USGS, 2010).

Due to the nature of cement manufacturing, cement production is an energy- and carbon-intensive process and therefore a major contributor to global anthropogenic CO_2 emissions. Cement production accounts for around 7% of total industrial fuel use, and almost 25% of total direct CO_2 emissions in industry (IEA, 2007). Of all industrial non-combustion processes, the cement clinker production process is the largest source of CO_2 emissions. It was estimated that in 2005, total direct and indirect CO_2 emissions from cement production were 1.9 Gt, which was almost 8% of total global CO_2 emissions, with more than 1.4 Gt emitted from cement kilns (IEA/WBCSD, 2006). The World Wildlife Fund (WWF) estimated that in 2006, the cement industry contributed to approximately 8% of the global anthropogenic CO_2 emissions or 6% of total manmade greenhouse gas emissions (WWF, 2008). It is expected that the market demand for, and production of, cement will continue to rise until 2050, which will almost certainly lead to a continuing increase in absolute CO_2 emissions.

In the past two decades, the cement industry has achieved significant decoupling of production growth and absolute CO_2 emissions. The global gross (all direct emissions) and net (gross CO_2 emissions minus alternative fossil fuels) CO_2 emissions in terms of kgCO_2/t clinker decreased by 5.3% and 6.9% respectively between 1990 and 2006. The gross and net CO_2 emissions per tonne of cementitious materials produced decreased by 10.6% and 12.1% respectively between 1990 and 2006 (WBCSD, 2009). Recently, IEA in collaboration with World Business Council for Sustainable Development (WBCSD) (IEA/WBCSD, 2009) developed a CO_2 emissions reduction technology roadmap for the cement industry. The roadmap raises the possibility of reducing total CO_2 emissions in the cement industry by 18% by 2050 providing the right regulatory framework, financing arrangements and infrastructure are put in place.

CO_2 emissions in cement manufacturing derive from two sources: fossil fuel combustion and the calcination of the principal limestone raw material. Over 50% of the CO_2 emissions in cement production result from calcination, and around 40% of the CO_2 result from combustion of the fossil fuels that supply the energy for calcination. Indirect CO_2 emissions due to the use of electricity that is generated by fossil fuel combustion account for about 5% of the total emissions. On average, between 0.8 and 0.9 tCO_2 is released into the atmosphere for every tonne of cement that is produced.

Climate change has become a prominent global issue, and governments are beginning to take significant steps to address the problem. The Kyoto Protocol sets binding targets for 37 industrialised countries and the European Union (Annex I countries) for reducing greenhouse gas emissions by 5% against 1990 levels over the five-year period of 2008 to 2012. The European Union is committed to reducing CO_2 emissions by 20% from 1990 levels by 2020. To achieve these goals, the cement industry as a key emission source will have to reduce the CO_2 emissions associated with cement production. Technologies and various measures are available to reduce CO_2 emissions from cement manufacturing.

The recent IEA roadmap envisages four levers for carbon emissions reduction from cement manufacturing: energy efficiency, alternative fuel, clinker substitution and carbon capture and storage (CCS). In addition to the four levers for reducing CO_2 emissions in cement production, extensive research is being carried out to develop innovative low-carbon cementitious materials as alternatives to the traditional Ordinary Portland Cement (OPC).

This report reviews the current state of the cement industry in terms of CO_2 emissions and possible mitigation strategies. The global and regional cement production and the related CO_2 emissions are reviewed in Chapter 2. The cement production processes and CO_2 emissions related to the cement manufacturing processes are presented in Chapter 3. As mentioned above, around 40% of total CO_2 emissions in cement production result from combustion of fossil fuels that supply the thermal energy for calcination. Improving the thermal energy efficiency in the clinker production process can reduce the energy consumption, associated costs and CO_2 emissions. A number of technologies and measures are available to improve the thermal energy efficiency of cement kilns and these are discussed in Chapter 4. The cement industry consumes around 1.5% of the total electricity produced globally (WWF, 2008). Most of the electricity is generated by combustion of fossil fuels leading to CO_2 emissions. Discussions on technologies and measures to improve electrical energy efficiency can be found in Chapter 5. The costs for implementing such technologies or measures, and the potential CO_2 savings are evaluated.

Coal is the most carbon-intensive fossil fuel and it is the most widely used fuel for firing kilns in the cement industry. Switching from high carbon-intensive fuels to less carbon- intensive fuels or replacing the conventional fuels with alternative fuels such as biomass and waste derived fuels may result in a significant reduction in CO_2 emissions. The materials that are suitable for firing in the cement kilns as alterative fuels, the benefits, technical challenges and limitations of using alternative fuels are discussed in detail in Chapter 6. Chapter 7 reviews the approach to CO_2 emissions reduction by clinker substitution. Clinker production is the most energy-intensive step in cement manufacturing and almost all of the direct CO_2 emissions come from the clinker burning process. Reducing the percentage of clinker in the finished cement is therefore the most effective way of reducing CO_2 emissions from cement production. Materials that may replace the cement clinker in the finished products, their applications, potentials and limitations are looked at in Chapter 7. The costs for implementing the clinker substituting materials and the potential CO_2 savings are assessed.

Over the years, cement manufacturers have made efforts to reduce fuel use, improve energy efficiency and use waste materials in cement production, leading to decreases in CO_2 emissions per unit of product. The scope for further reductions by these means is limited. Any further significant reductions in CO_2 emissions by the cement industry will depend on the development of CCS (carbon capture and storage) technologies and/or innovative, low-carbon cementitious materials. CCS is a key strategy for decarbonising energy-intensive industries including cement manufacturing. Chapter 8 examines the carbon capture technologies potentially applicable to cement manufacturing. The status and costs of these technologies are discussed.

As mentioned above, the CO_2 formed and released during the calcination of the traditional limestone raw material accounts for over 50% of the total CO_2 emissions in cement production and there is no technological or physical way to reduce the process emissions. However, if the calcination step could be changed, or even removed altogether, it may then be possible to achieve significant further reductions in CO_2 emissions. Extensive research is being carried out to investigate new methods or innovative processes for making low-carbon cementitious materials. A large number of potential Ordinary Portland Cement (OPC) replacements and substitutes are being developed and some of these are described in Chapter 9. The approach to reducing the emissions of process CO_2 by replacing limestone in the clinker raw feed with raw materials with low embodied CO_2 is also discussed.

2 Cement production and related CO_2 emissions

2.1 Cement production

World cement production has been increasing steadily over many decades amounting to around 2.31 Gt in 2005 (USGS, 2010). Based on the data from Taylor (2006) and the WWF (2008), this represented an increase of over 283% from the 1970s production level and almost double the total production in 1990. This was also a 44.4% increase from the world total cement output of 1.6 Gt in 2000 (USGS, 2010). The regional and the global cement production from 1994 to 2008 are shown in Figure 1, and the source data are given in Table 1.

Figure 1 clearly shows that the world total cement output has been increasing, and this increase has accelerated since 2000. This accelerated increase in cement production coincides with a period of strong economic growth in some developing countries, especially China and India. However, global cement volumes (excluding China) were down by almost 6% in 2009 due to the global economic downtown caused by the credit crunch, but looked set to recover in 2010 to increase by 4.1%. The forecast for 2011 is for a further increase of 6%, excluding China (Maxwell-Cook, 2010).

Growth remains strong in the emerging markets, and the highest growth rates in 2009 were observed in China, India and some countries in Africa and the Middle East (Maxwell-Cook, 2010). It is evident from Table 1 that Asia, which has the most populated regions and fastest growing economies of the world, has seen the strongest increase in cement demand and production. In 2005, the share of Asian cement production in the world reached 68% (WWF, 2008). Other emerging economies like Brazil
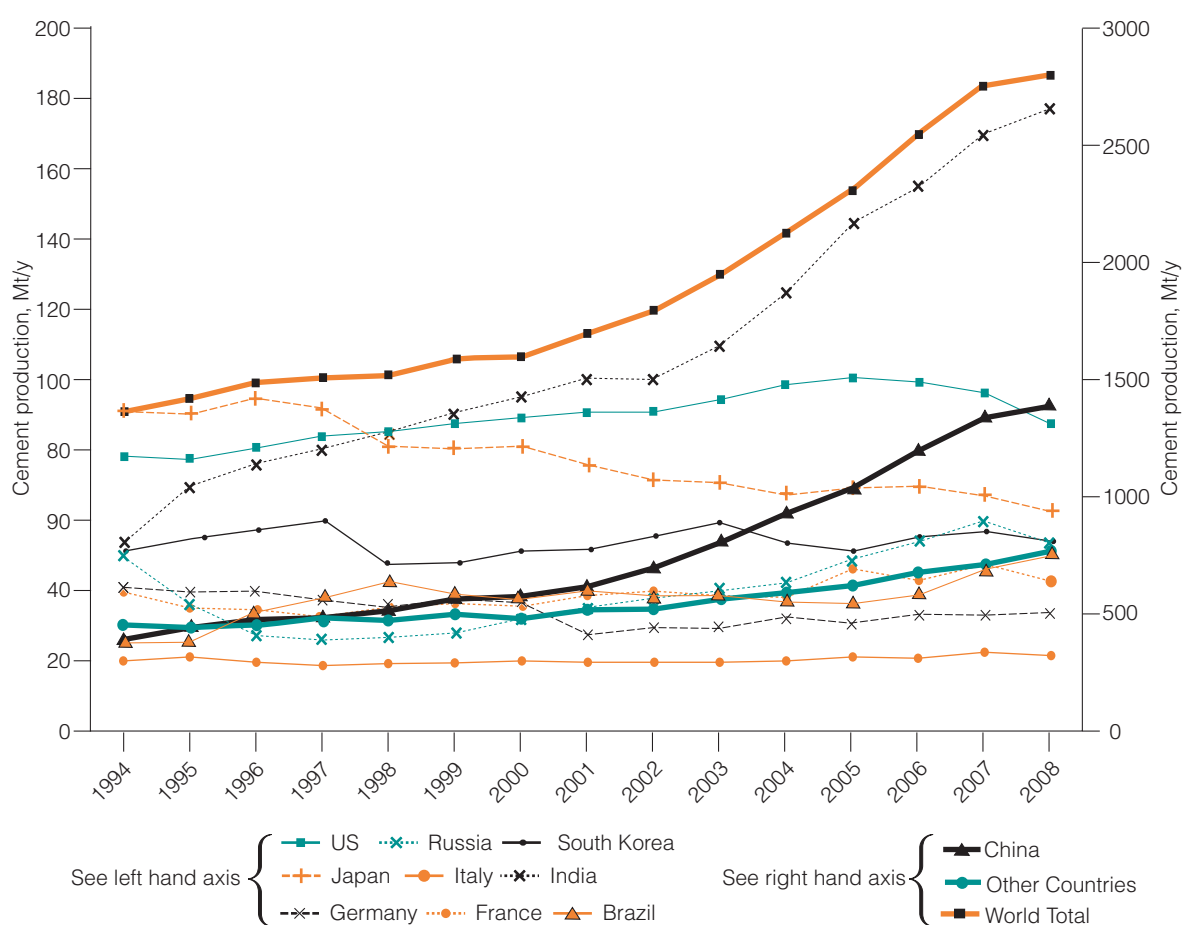
Figure 1   Cement production

Table 1   Cement production, Mt/y

Year	USA	Brazil	China	France	Germany	India	Italy	Japan	S Korea	Russia	Spain	Turkey	Other countries	World total
1994	77.9	26	400	20.2	40.4	5.4	40	91.5	52.1	50	26	30	461	1370
1995	78.32	25.5	445.61	21	40	70	35	90.474	55.13	36.4	25	33.163	441.778	1421.3
1996	78.32	85.612	490	20	40	76.22	34	94.492	57.334	27.8	25.157	32.5	471.646	1485
1997	84.255	38.096	492.6	19	37	80	33.721	91.938	59.796	26.6	27.632	36.035	490.07	1515
1998	87.777	43	513.5	19.5	36.61	85	35	81.328	46.791	26.726	27.943	38.2	478.485	1520
1999	89.51	40.27	573	19.527	38.099	90	36	80.12	48.157	28.4	30.8	34.403	503.196	1600
2000	90.45	39.208	583.19	20	38	95	36	81.3	51.255	32.4	30	35.825	484.109	1600
2001	91.3	39.5	626.5	19.839	28.034	100	39.804	76.55	52.012	35.1	40.512	30.12	521.737	1700
2002	94.3	39.5	705	20	30	100	40	71.8	55.5	37.7	42.5	32.6	529.8	1800
2003	99	38	813	20	30	110	38	71	59.2	41	42	33	561.6	1950
2004	101	38	934	21	32	125	38	67.4	53.9	43	46.8	38	594.1	2130
2005	99.7	36.7	1040	21.3	30.6	145	46.4	69.6	51.4	48.7	50.3	42.8	627.7	2310
2006	96.5	39.5	1200	21	33.4	155	43.2	69.9	55	54.7	54	47.5	677.1	2550
2007	87.6	46.4	1350	22.3	33.4	170	47.5	67.7	57	59.9	54.5	49.5	716.6	2770
2008	87.6	51.9	1390	21.7	33.6	177	43	62.8	53.9	53.6	42.1	1.4	771.4	2800

and Turkey have also seen significant increases in cement demand and production. On the other hand, all industrialised countries together accounted for less than 25% of the world cement production in 2005 and the average annual growth rate was well below 2% (WWF, 2008). As shown in Table 1 the cement demand and production in developed countries such as France and Germany are stable over the time span and this trend is expected to continue.

Figure 2   The past, present and forecasted cement production (WWF, 2008)

China and India remain at the forefront of expansion and development in the cement industry. Figure 2 shows the past, present and forecast regional and world cement production. It can be seen from Figure 2 that in recent years the vast majority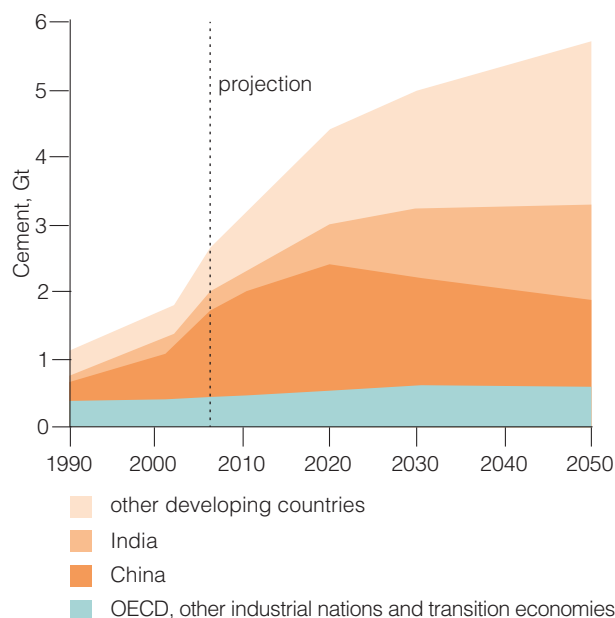 of the growth in cement production occurred in rapidly developing countries, especially China. China is currently the world's largest cement producer. In 2006, China manufactured 1.2 Gt cement, accounting for more than 47% of the world total cement production in that year. China's annual growth rate of cement production had been kept at around 10% over two decades till 2007. Due to the impacts of the credit crunch in the western countries on China's economy, China's cement output in 2008 was 1.4 Gt, a 2.9% increase from the 1.36 Gt cement produced in 2007 (NBSC, 2009). However, China's cement production is picking up strongly and it is now growing even faster. According to recent data published by the National Bureau of Statistics of China, China produced 335.9 million tonnes (Mt) of cement in the first quarter of 2010, which was an increase of 20.3% over the same period in the previous year (NBSC 2010). China's cement demand will continue to be high in the near future and it is predicted that China's cement production will peak at around 1.85 Gt around the year 2020 (WWF, 2008).

India has recently become the world's second largest cement producer after China. The Indian cement industry witnessed rapid expansion for over two decades. The total cement production in India for the year ended March 2009 was over 198 Mt (Singhi and Bhargava, 2010), up by 17.6% from the 168.31 Mt produced in the previous year (India Cements, 2010). The structure of the Indian cement industry is highly fragmented, with the capacity of cement plants varying from 10 to 7500 tonnes per day (t/d). The large plants account for approximately 94% of the production capacity and more than 95% of total production in India (Mandal and Madheswaran, 2010). Table 2 shows the cement production capacity, annual output and growth rate of the large cement plants in India from 1981 to 2009. It should be noted that the statistics of the annual production were for the Indian fiscal year which is from 1 April to 31 March. It can be seen from Table 2 that India's cement output has been increasing since the 1980s. Between 2005 and 2009, India's cement production grew at an average rate of more than 11%.

India is the second largest populated country in the world and has one of the world's fastest growing economies. Based on the gross domestic production (GDP) figures published on the official website (http://mospi.nic.in/) of the Ministry of Statistics and Programme Implementation, India, the average annual GDP growth rate between 2001 and 2009 is 6.9%. It is expected that India's economy will continue to grow at this fast pace for the foreseeable future. Driven by the strong economic growth, increasing population and continued urbanisation, the cement demand and production in India are predicted to expand rapidly for the next several decades. The Indian cement industry is now

Table 2	Cement production capacity, output and growth rate of large plants in India (The India Cements Ltd, 2010; Singhi and Bhargava, 2010)		
	Capacity at the end 2001, Mt/y	Annual production, Mt/y (30 Mar 2011)	Growth rate %
1981	28.93	20.77	
1982	31.78	22.54	8.5
1983	35.86	25.41	12.7
1984	39.10	29.14	14.7
1985	41.85	31.11	6.8
1986	49.10	33.65	8.2
1987	54.51	36.97	9.9
1988	55.04	40.72	10.1
1989	56.36	42.07	3.3
1990	58.12	44.87	6.7
1991	60.61	49.47	10.3
1992	62.46	50.87	2.8
1993	66.90	52.78	3.8
1994	73.19	57.57	9.1
1995	82.06	62.08	7.8
1996	90.17	68.86	10.9
1997	99.92	74.75	8.6
1998	108.41	79.42	6.2
1999	109.44	91.72	15.5
2000	116.82	95.95	4.6
2001	133.55	98.35	2.5
2002	137.53	109.59	11.4
2003	140.07	111.35	1.6
2004	146.38	117.50	5.5
2005	153.59	127.57	8.6
2006	157.59	141.8	11.2
2007	165.4	155.66	9.8
2008	190.45	168.31	8.1
2009	206.7	198	17.6

expanding so fast that it is projected that by 2050, India's total annual cement output will be similar to that of China or even larger as seen in Figure 2.

Several other emerging economies such as Brazil, Mexico, Turkey, Vietnam, Egypt and Iran have also experienced strong increases in cement demand and production in recent years (USGS, 2010). It is expected that these countries will continue to see a massive expansion of their cement markets. With cement demand and production being stable in the developed countries but fast growing in the developing countries, the global cement output will continue to increase. It is predicted that the stabilisation of global cement production is unlikely to occur before 2050 (*see* Figure 2) and by then the output level will be more than twice the current levels (WWF, 2008).

2.2 CO_2 emissions

2.2.1   Global and regional CO_2 emissions

Global CO_2 emissions more than doubled between 1971 and 2007. Anthropogenic CO_2 emissions data from sovereign states and territories are published by the United Nations at http://mdgs.un.org/unsd/mdg/SeriesDetail.aspx?srid=749&crid=. It can be concluded from these data that, in 2007, global total CO_2 emissions due to human activities were more than 29.3 Gt. In 2009, total global CO_2 emissions were estimated to be 31.3 Gt, which represented an increase of 25% since 2000 and almost a 40% increase since 1990 (Olivier and Peters, 2010). Figure 3 shows the estimated CO_2 emissions from the world's top 25 largest emitting countries in 2008 and 2009. The relative contributions from major world regions to the global CO_2 emissions in certain years are shown in Figure 4. In 2009, the shares of the CO_2 emissions from developing countries were 53% of the global total compared to 44% for developed countries. The world's top five largest emitters China, USA, India, Russia, Japan plus the EU-15 countries comprise two-thirds of total global emissions whereas the top-25 emitting countries emitted more than 80% of the world total (Olivier and Peters, 2010).

2.2.2 CO_2 emissions from the cement industry

Carbon dioxide, the primary greenhouse gas that drives global climate change, is the only greenhouse gas emitted by the cement industry in a significant amount. Producing cement co-produces CO_2, both directly from fossil fuel combustion in the kiln and from the calcination process of the raw material
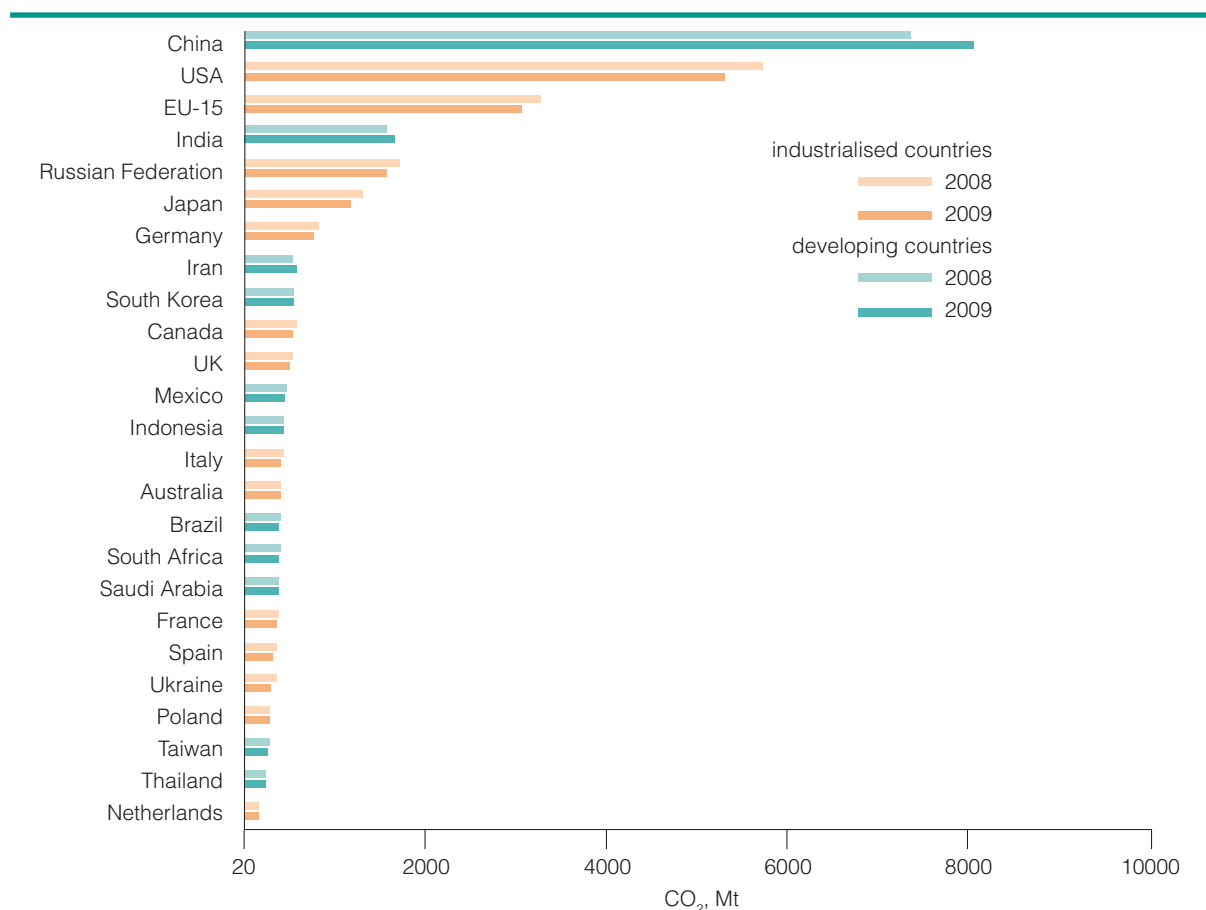
Figure 3 CO_2 emissions from the world top 25 emitters in 2008 and 2009 (Olivier and Peters, 2010)

(mainly limestone), as well as indirectly from consumption of electricity, assuming that the electricity is generated from fossil fuel combustion. A study commissioned by the World Business Council for Sustainable Development (WBCSD, 2002a) estimated that in 2000 the cement industry emitted around 1.4 $GtCO_2$, which accounted for approximately 5% of the global anthropogenic CO_2 emissions or 3% of the global anthropogenic greenhouse gas emissions. In 2005, the total CO_2 emissions (direct and indirect) from cement production increased to 1.9 Gt, which was almost 8% of total global CO_2 emissions, with more than 1.4 Gt emitted from cement kilns (IEA/WBCSD, 2006). The WWF estimated that in 2006, the cement industry contributed approximately 8% of the global anthropogenic CO_2 emissions or 6% of total man-made greenhouse gas emissions (WWF, 2008).

In 2007 to 2008, the Cement Sustainability Initiative (CSI), operating under the umbrella of WBCSD, developed the 'Getting the Number Right' (GNR) system which is a CO_2 and energy performance information system based on emissions data from individual cement plants of GNR's members. The GNR system includes information from 844 cement installations worldwide, covering over 73% of cement production in Annex I countries and around 20% of cement production in non-Annex I countries (WBCSD, 2009). Overall, the GNR database covers around 31% of the global total cement production. The gross direct CO_2 emissions from cement production of all GNR participants from 1990 to 2006 are shown in Figure 5. It can been seen from Figure 5 that the CO_2 emissions by GNR members in Annex I countries remained almost unchanged despite the 10% increase in the cement production in those countries between 1990 and 2006. The decoupling of CO_2 emissions and cement production is an indication of improved emissions efficiency in the developed countries. The CO_2 emissions from cement production in non-Annex I region, however, increased significantly from 1990 to 2006, corresponding to the rapid expansion in cement production in developing countries.

China is currently the world's largest cement producer and CO_2 emitter. In 2006, the building materials

Notes for Figure 4:

* The original Annex II parties to the United Nations Framework Convention on Climate Change (UNFCCC) are Australia, Austria, Belgium, Canada, Denmark, EC, Finland, France,Germany, Greece, Iceland, Ireland, Italy, Japan, Liechtenstein, Luxembourg, Monaco, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, UK and USA. Turkey was removed from Annex II on 28 June 2002.

† Annex I EIT parties include Belarus, Bulgaria, Croatia, Czech Republic, Slovak Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Russia, Slovenia and Ukraine.

‡ Asia includes Korea but excludes Japan.

¶ Other includes Africa, Latin America, Middle East, non-Annex I EIT, Turkey, international bunkers, and for 1971, Annex I EIT.

Figure 4   Trends in regional CO_2 emissions (IEA, 2009)

Figure 5   Absolute gross direct CO_2 emission from the GNR members by region (WBCSD, 2009)

Table 3	Output, energy consumption and direct CO_2 emissions in Chinese cement industry in 2006 (IEA, 2007)		
Output, Mt	Fuel consumption, PJ/y	Power consumption, TWh	Direct CO_2 emission, Mt/y
1235	3047	123.5	986

Table 4	Recent trend of process CO_2 emissions, Mt from US cement production (EPA, 2010a)					
1990	1995	2000	2005	2006	2007	2008
33.3	36.8	41.2	45.9	46.6	45.2	41.1

industry in China used 6.6 EJ of fossil fuels and 0.8 EJ of electricity, which equals about 6% of all manufacturing industry final energy use and 23% of CO_2 emissions. China's cement production accounted for half of this energy use and three-quarters of CO_2 emissions (IEA, 2007). Table 3 shows the total output, energy consumption and direct CO_2 emissions in the Chinese cement industry in 2006.

In the USA, clinker production totalled 79.6 Mt in 2008 and the resulting CO_2 emissions were estimated to be 41.1 Mt (EPA, 2010a). The recent trend of process CO_2 emissions from US cement production is shown in Table 4. After falling in 1991 by 2% from 1990 levels,
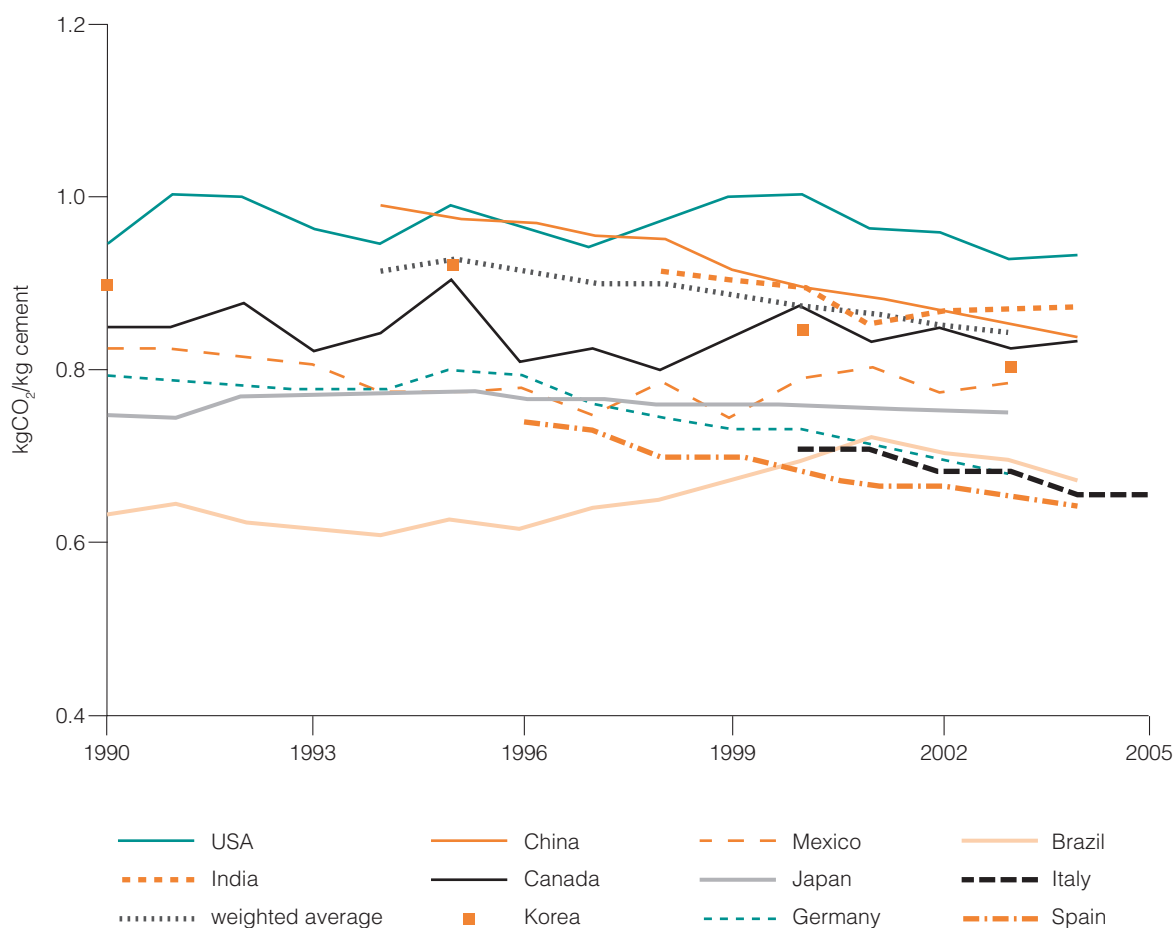
note: Includes impact of electricity generation from waste heat in Japan.
Boundary definitions may differ by country

Figure 6   Unit-based total CO_2 emissions from cement production by countries from 1990 to 2005 (IEA, 2007)

CO_2 emissions from cement production in the USA grew every year through 2006, and then decreased from 2006 to 2008. Overall, CO_2 emissions in the US cement industry increased by 24% from 1990 to 2008.

CO_2 emissions from the cement industry in Europe peaked in 2007 at 173.6 $MtCO_2$. However, CO_2 emissions from the European cement industry fell in 2008 to 157.8 Mt, which was similar to their 2005 level (157.4 $MtCO_2$) (SETIS, 2009).

CO_2 emissions per tonne of cement produced (unit-based emissions) can be used as an indicator for the energy and CO_2 performance of cement production. It varies from plant to plant depending on the clinker production process used, fuel type, and many other factors. Figure 6 shows the unit-based total (both direct and indirect) CO_2 emissions by country from 1990 to 2005. Figure 6 shows a general decrease in the CO_2 intensity of cement production over the years in most countries. Significant improvements in the CO_2 intensity of cement production are seen in countries such as China, Germany, Italy, Korea and Spain. Total CO_2 emissions per tonne of cement produced in 2003 to 2004 ranged from about 0.65 $kgCO_2$/kg of cement in Spain, Brazil and Italy to 0.93 $kgCO_2$/kg of cement in the USA (IEA, 2007).

2.3   Comments

Due to the unique nature of cement manufacturing, cement production is a key source of CO_2

emissions. Despite both the GNR data that show a partial decoupling of CO_2 emissions and cement production from its participants and the IEA data of decreased overall unit-based CO_2 emissions indicating improved CO_2 emissions performance of cement production in general (WBCSD, 2009; IEA, 2007), the absolute CO_2 emissions from cement production have increased significantly due to the rapid expansion in total global cement production. From 2000 to 2006, global cement production increased by 54%, resulting in an increase in absolute direct CO_2 emissions by an estimated 42% (560 Mt) reaching 1.88 Gt in 2006 (IEA/WBCSD, 2009). The growth of market demand for, and production of, concrete and cement are expected to continue until 2050, which will lead to a continued increase in absolute CO_2 emissions.

Climate change has become a prominent global issue, and governments are beginning to take significant steps to address the problem. The Kyoto Protocol, which was adopted in Kyoto, Japan, on 11 December 1997 and entered into force on 16 February 2005, sets binding targets for 37 industrialised countries and the European Union (Annex I countries) for reducing greenhouse gas emissions by 5% against 1990 levels over the five-year period of 2008 to 2012. The European Union is committed to reducing CO_2 emissions by 20% from 1990 levels by 2020. To achieve these goals, the cement industry as a key emission source will have to reduce the CO_2 emissions associated with cement production. Technologies and various measures are available to reduce CO_2 emissions from cement manufacturing. The technology roadmap for the cement industry developed by the IEA (IEA/WBCSD, 2009) described the possibility of reducing total CO_2 emissions in the cement industry by 18% by 2050. The IEA (2007) estimated that the potential CO_2 emissions reduction in the cement industry from the use of best available technology, the increased use of clinker feedstock substitutes in the kiln and the use of more clinker substitutes in finished cement would be between 480 and 520 $MtCO_2$. However, these savings could not be achieved in the short to medium term without significant economic costs. Any further significant reductions in CO_2 emissions in the cement industry will depend on the development of CCS (carbon capture and storage) technologies and/or innovative cementitious materials with low embodied CO_2.

3 Cement manufacturing processes

Cement is an inorganic, non-metallic substance with hydraulic binding properties. It is a fine powder, usually grey in colour. Mixed with water it forms a paste that hardens due to formation of cement mineral hydrates and therefore is used as a binding agent in concrete and other building materials. The main component of cement is clinker. Clinker is produced from raw materials such as limestone and clay. Cement plants are typically constructed in areas with substantial raw materials deposits. Limestone extracted from a quarry is transported to a cement plant where the limestone rocks are fed into a crusher and broken into smaller pieces. The crushed limestone pieces are then mixed with other raw materials such as clay, shale, sand, quartz or iron ore in different proportions to create cements with specific chemical compositions and the mixture is milled together to produce the 'raw meal'. The raw meal is then pyro-processed in a kiln to produce clinker. The clinker from the kiln is cooled and other materials such as gypsum are added to the clinker. All constituents are ground together to form a fine and homogeneous powder: cement. Figure 7 shows a schematic of the simplified cement making process.
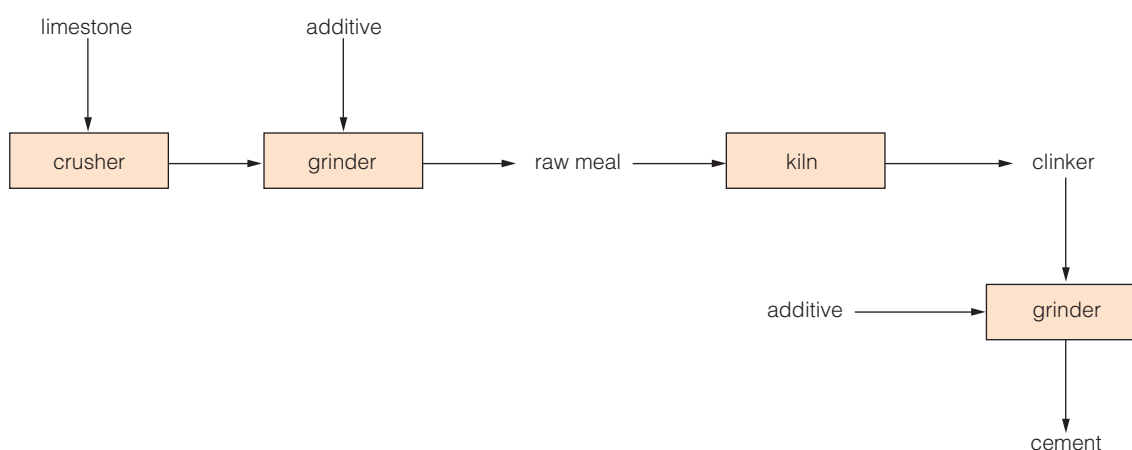
Figure 7   A schematic of the simplified cement making process

Two different processes, dry and wet, are used in the manufacture of cement. At each stage of cement making, various processes/technologies are employed by individual cement plants. A brief overview of the commonly used cement production processes and their energy use is given in the following sections. A detailed description of the applied processes and technologies in cement industry can be found elsewhere (EIPPCB, 2010).

3.1   Raw material preparation

The first step in the manufacture of cement is crushing. Boulder-size limestone rocks are first reduced to a maximum size of about 15 cm in primary crushers. The rock then goes to secondary crushers for reduction to about 7.5 cm or smaller. The limestone pieces then go through a blender where they are added to the other raw materials in the correct proportion.

In the wet process, the raw material, properly proportioned by mixing with other materials such as clay and sand, is fed to a mill with water where the raw materials are ground further. The raw material, exiting the mill in a form of slurry, is thoroughly mixed and homogenised and made ready to be fed into the kiln. The water content of a slurry is generally in the range of 24% to 48%. A semi-wet process with a slurry containing 17% to 22% water is also used to reduce the fuel consumption in the kiln (Worrell and Galitsky, 2008).

In the dry process, the raw material is proportioned by adding to it other materials to meet a desired chemical composition. The mixture is then fed to a mill in which the materials are dried if necessary and ground to a powder. The dry, powdery material exiting the mill is called 'kiln feed'.

Raw material preparation is an electricity-intensive process. The total energy consumption of this process depends on factors such as if a dry or wet process is used, the type of crushers and grinding mills used, the moisture content of the raw material (if drying is necessary in a dry process) and the hardness of the raw materials. The energy used in preparing the raw material is generally in the range of 25 to 35 kWh/t of raw material (Worrell and Galitsky, 2008). However, if overall best practice is adopted the energy consumption for raw material preparation can be reduced to around 12.05 kWh/t (0.04 GJ/t) of raw material (Worrell and others, 2008a).

3.2 Clinker production (pyro-processing)

There are a number of different kiln types. Whether the process is wet or dry, the same chemical reactions take place in the kiln. Most cement is made in a rotary kiln. The raw meal is fed into a rotating kiln in which it is heated to a temperature as high as 1500ºC. The kiln is a gently sloped steel cylinder, lined with special refractory materials to protect it from the high process temperatures, and it turns slowly (a few revolutions per minute). Fuels such as pulverised coal, natural gas, fuel oils and petroleum coke are burned to feed a flame projected up-kiln from a burner tube inserted into the lower end of the kiln to produce the heat required for calcination. The rotation causes the raw meal to gradually pass along from where it enters at the cool end, to the hot end where the material becomes partially molten and it eventually drops out and cools. The intense heat triggers the chemical and physical changes that transform the raw feedstock into cement clinker.

3.2.1 Wet process

In the wet process, the slurry is fed to a rotary kiln, which can be from 3 to 5 m or larger in diameter and more than 200 m in length. Wet kiln feed typically contains more than 30% water. This water must be evaporated in the specially designed drying zone at the inlet section of the kiln where a substantial portion of the heat from fuel combustion is used. As a result, the wet process has a significantly higher energy consumption than the dry process. The evaporation step also makes a long kiln necessary.

Originally, the wet process was the preferred process as it was easier to mix, grind and control the size distribution of the particles in a slurry form. With the development of improved grinding and mixing technologies, and improvements in the energy efficiency of pyro-processing kilns, modern cement plants use a dry-rotary kiln with multistage preheaters and pre-calciners. The need for the wet process has been reduced. However, the wet process has survived for over a century because many raw materials are suited to blending as a slurry. Today, a number of wet process kilns are still in operation, especially in regions where only wet raw materials are available. Depending on the water content of the raw meal and the thermal efficiency of the kiln, fuel use in a wet kiln can vary between 5.3 and 7.1 GJ/t clinker (Worrell and Galitsky, 2008).

3.2.2 Dry process

In the dry process, kiln feed is fed to a preheater or pre-calciner kiln or, more rarely, to a long dry kiln. The dry rotary kiln can have the same diameter as a wet process kiln but the length is much shorter at approximately 45 m. The preheater or pre-calciner kilns have tall preheater towers. These towers use the heat from the kiln to preheat the raw materials. A benefit of these kilns is their fuel efficiency. They use much less energy than the long dry kiln. Today's state-of-the-art dry rotary kilns are fairly

fuel efficient making them the likely technology of choice for several decades. The thermodynamic minimum to drive the endothermic reactions is approximately 1.8 GJ/t clinker for dry feedstock, but is much higher for feedstock with significant moisture content (IEA, 2007).

3.2.3 The clinker cooler

The rotary kiln discharges the red-hot clinker into a clinker cooler. The clinker cooler is an integral part of the kiln system and has two tasks: 1) to recover as much heat as possible from the hot clinker and return it to the process; 2) to reduce the clinker temperature to a level suitable for the equipment downstream. The clinker cooler has a decisive influence on the performance and economy of the clinker making process. There are two main types of cooler: rotary and grate cooler.

3.3 Finishing grinding

Clinker is ground together with gypsum and other mineral components in mills to form the final cement products. Grinding clinker and gypsum together forms a grey powder called Ordinary Portland Cement (OPC), whilst clinker mixed with other mineral components makes blended cement. The fineness of the final products, the amount of gypsum added, and the amount of process additions added are all varied to develop the desired performance in each of the final cement products. Grinding clinker requires a lot of electrical energy. Grinding mills (raw grinding and finishing grinding) are the largest electricity users in the cement industry. Raw and finishing grinding and the exhaust fans (kiln/raw mill and cement mill) together account for more than 80% of electrical energy usage in cement production. Currently about 100 kWh/t cement is consumed in rotary kilns for grinding raw materials, at the kiln and for grinding cement (IEA, 2007). The electricity use can vary significantly from plant to plant and is determined by factors including grinding technique used, the grindability of clinker, the fineness of the final product required and the amount and properties of the additives. Worrell and others estimated that the best practice for cement grinding would have an energy demand in the range between 16 and 19.8 kWh/t cement (Worrell and others, 2008a).

3.4 Related CO_2 emissions in the cement manufacturing process

It is estimated that the production of one tonne of cement releases 0.73 to 0.99 tCO_2 in different regions of the world (WWF, 2008). IEA (2007) reported that in 2005 the world average was 0.83 tCO_2/t cement with a range of 0.65 to 0.92 tCO_2/t cement. CO_2 emissions in cement manufacturing derive from two sources: energy consumption and the calcination of the principal calcium carbonate raw material.

CO_2 emissions from calcination (process emissions)

The raw material is heated in the kiln to above 1450ºC and this intense heat triggers the chemical and physical changes that transform the raw material into clinker. At around 900ºC, the limestone ($CaCO_3$) undergoes a chemical reaction called 'calcination' during which process CO_2 is released and calcium oxide (CaO) is formed. The main reaction is:

$$CaCO_3 \rightarrow CaO + CO_2$$
$$\text{(1 kg)} \quad \text{(0.56 kg)} \quad \text{(0.44 kg)}$$
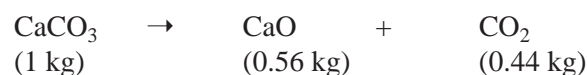
From the above reaction formula it can be calculated that the calcium carbonate calcining reaction releases 0.786 tCO_2 for per tonne of CaO produced. There is no technological or physical way to reduce the process emissions. Many clickers contain about 60– 67% CaO. Therefore, the calcination process produces roughly 0.47–0.53 tCO_2 for each tonne of clinker (t clinker) manufactured. The process emissions typically make up more than 50% of the total direct CO_2 emissions in cement

production. They show very small variations between plants and regions, and are unlikely to be reduced significantly.

CO_2 emissions from energy use

CO_2 emissions from energy use can be divided into direct emissions from combustion of fuels to provide the thermal energy necessary for calcination to occur and indirect emissions from consumption of electricity assuming that the electricity is generated from fossil fuel combustion. The direct CO_2 emissions from the combustion of fuel are highly dependent on the energy efficiency of the kiln and the fuel mix used. Approximately 40% of the CO_2 released during cement manufacturing is the result of fossil fuel combustion in the kiln. The contribution of indirect CO_2 emissions due to the use of electricity to the total emissions can vary from less than 1% to over 10% depending on the local electricity mix and the efficiency at which it is used. On average, 100 to 110 kWh electricity is consumed for per tonne of cement (t cement) produced leading to 5% indirect CO_2 emissions (WWF, 2008).

Recently, IEA in collaboration with WBCSD (IEA/WBCSD, 2009) developed a CO_2 emissions reduction technology roadmap for the cement industry. The roadmap envisages four levers for carbon emissions reduction in cement manufacturing:
1   Improving energy (thermal and electric) efficiency.
2   Replacing traditional carbon-intensive fossil fuels with less carbon-intensive fossil fuels, biomass fuels and/or wastes.
3   Substituting carbon-intensive clinker, an intermediate in cement manufacture, with other, lower carbon materials with cementitious properties.
4   Carbon capture and storage (CCS).

In addition to the above mentioned four levers for CO_2 emissions reduction, work is being carried out to develop low-carbon or even carbon-negative cements. The following chapters of this report will provide detailed discussions on the potential options for carbon emissions reduction in the cement industry.

4 Thermal energy efficiency

Cement making is an energy-intensive industry. The total energy consumption of individual cement plants is dependent on the process/technologies used and consists of mainly two parts: combustion of fossil fuel to provide the process heat required for calcination (thermal energy) and electricity to run the machinery (electrical energy). Energy use accounts for around 40% of the cement production cost. The consumption of electrical energy accounts for approximately 20% of cement energy needs (SETIS, 2009). Improving energy efficiency can result not only in significant CO_2 emissions reductions in cement production, but also a cost advantage to cement manufacturers through lower energy costs. Over the past 20 years, the European cement industry has reduced its energy consumption by about 30%, which is equivalent to saving approximately 11 Mt/y of coal (Holcim/GTZ, 2006). Price and Worrell (2006) estimated that a potential 8% to 28% of CO_2 emissions reduction could be achieved through improving energy efficiency.

Most of the CO_2 emissions and energy use of the cement industry are related to the production of the clinker. Clinker production is the most energy-intensive step, accounting for around 80% of the energy used in cement manufacturing. According to EIPPCB (2010) today's state of the art cement kiln processes can achieve a thermal efficiency of 2.9 to 3.3 GJ/t clinker. The WBCSD reckons that the thermal energy consumption of modern, dry process cement kilns is approximately 3.4 GJ/t clinker (3383 MJ/t) (Clark, 2010). The theoretical thermal (fuel) energy demand for cement clinker production is determined by the energy required for the chemical/mineralogical reactions of calcination and clinkering process and for raw material drying. The thermal energy required to drive the endothermic reactions is in the range of 1.7 to 1.8 GJ/t clinker which cannot be decreased, whilst the thermal energy used for drying depends on the moisture content of the raw material and ranges from 0.2 to 1.0 GJ/t clinker (based on a moisture content of 3% to 15%), and the rest are thermal losses (SETIS, 2009). A vast number of cement kilns in operation worldwide do not come close to the optimum thermal energy efficiency figures given by EIPPCB and WBSCD. As a result, this leaves ample opportunity for improving the thermal efficiency of cement kilns and therefore significant reductions in CO_2 emissions.

4.1 Cement kiln technologies

4.1.1 Development of cement kiln technologies

The first rotary kilns were long wet kilns where the whole heat consuming thermal process takes place in the kiln itself. The first development of a dry process was the long dry kiln without preheating. Later developments led to technologies using rotary kilns with multistage cyclone preheaters or shaft preheaters. In a preheater kiln the drying, preheating takes place in a stationary installation rather than in the rotary kiln. In theory, shaft preheaters have superior heat exchange properties. However, the difficulty of ensuring an even distribution of meal to gas meant that actual performance was far worse than expected. Consequently, this technology was eventually abandoned in favour of multistage cyclone preheaters (EIPPCB, 2010). More recently the pre-calciner technology was developed in which a second combustion chamber is added between the kiln and a conventional preheater (Worrell and Galitsky, 2008).

In some parts of the world, vertical shaft kilns are used for cement production. A shaft kiln consists of a refractory-lined, vertical cylinder 2–3 m in diameter and 8–10 m high. The raw meal and fuel are fed to the kiln from the top and the material is burned while travelling through a short sintering zone in the upper, slightly enlarged part of the kiln. The material is then cooled by the combustion air blown in from the bottom and leaves the lower end of the kiln in the form of clinker. Shaft kilns are relatively

inefficient compared to a dry rotary kiln and have small production capacity. They are only economic for small cement plants, and for this reason their number has been diminishing (EIPPCB, 2010).
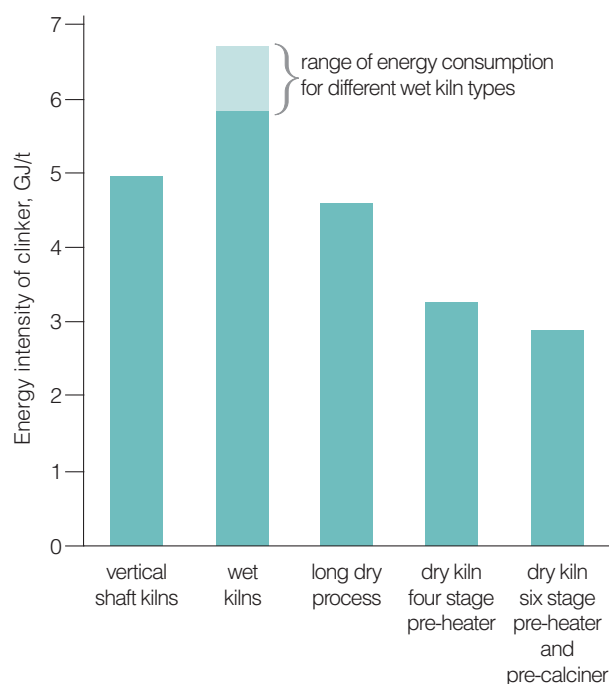

Figure 8   Energy efficiency of various kiln technologies (IEA, 2007)

The energy intensity of various cement kiln technologies is shown in Figure 8. The wet process is energy inefficient and can consume twice as much energy as a modern dry process cement kiln. For the dry process, the long dry kiln has lower energy intensity than a vertical shaft kiln. Adding preheaters to the dry rotary kiln reduces its fuel requirements. Using pre-calciner technology further reduces the kiln fuel requirements and is therefore more energy efficient.

Cement clinker production is the main energy consuming process in the industry and the actual fuel demand for clinker production depends on the kiln system used and the kiln size. Table 5 shows the fuel consumption of different kiln technologies. It is evident from Table 5 that the wet process kilns have the highest thermal energy consumption. This is followed by vertical shaft kilns, of which there are three main types consuming between 4.8 and 6.7 GJ/t clinker. The thermal energy consumption of semi-wet/semi-dry processes is in the range between 3.3 and 5.4 GJ/t compared to the long dry kilns that require around 4.6 GJ/t clinker. Using preheaters and pre-calciners improves the fuel efficiency of the cement kiln but slightly increases its electricity consumption. It has been reported that the best performing cement kiln has a fuel consumption as low as 2.7 GJ/t clinker. Today's state-of-the art cement kiln is the dry kiln process with multistage (four to six stages) cyclone preheaters with an integral pre-calciner and tertiary air duct, which can achieve a thermal efficiency of 2.9 to 3.3 GJ/t clinker when operating under optimised conditions (EIPPCB, 2010). The modern kilns with preheaters and pre-calciner have a larger production capacity than older installations, which also contributes to higher energy efficiency (WBCSD, 2009).

Table 5	Fuel consumption of different kiln technologies (IEA, 2007; EIPPCB, 2010)
Process	Fuel consumption, GJ/t clinker
Wet process	5.0–6.7
Semi-wet/semi-dry processes	3.3–5.4
Dry process shaft kiln	4.8–6.7
Long dry kiln	4.6–5.3
1 stage cyclone preheater	4.2
2 stage cyclone preheater	3.8
3 stage cyclone preheater	3.3
4 stage cyclone preheater + pre-calciner	3.1
5 stage cyclone preheater + pre-calciner	3.0–3.1
6 stage cyclone preheater + pre-calciner	2.9

4.1.2 Implementing the best available technologies

Table 6 Cement kiln processes used in different countries and regions (IEA, 2007)	Process type			
	Dry, %	Semi-dry, %	Wet, %	Vertical, %
Canada	71	6	23	0
USA	82	1	18	0
Brazil	98	N/A	N/A	N/A
Latin America	67	9	23	1
Europe	92	4.5	3.5	0
Former Soviet Union	12	3	78	7
China	50	0	3	47
India	50	9	25	16
Japan	100	0	0	0
South Korea	93	0	7	0
Southeast Asia	80	9	10	1
Australia & New Zealand	24	3	72	0
Africa	66	9	24	0
Middle East	82	3	16	0

The thermal efficiency of an installation is largely defined by its original engineering design and the process chosen, which are both dependent on the technologies available at the time the plant was built. Therefore, older cement kilns generally have higher thermal energy consumption compared with more recent installations. There are large regional differences in thermal efficiencies of cement kilns in operation due to the varying ages of the installations and technologies applied in each region. Table 6 shows the cement kiln technologies used in some individual countries and regions, and the average thermal efficiencies over the years at regional and global levels (based on data from GNR participants) are shown in Figure 9. In the Former Soviet Union, most kilns are quite old and still use the inefficient wet
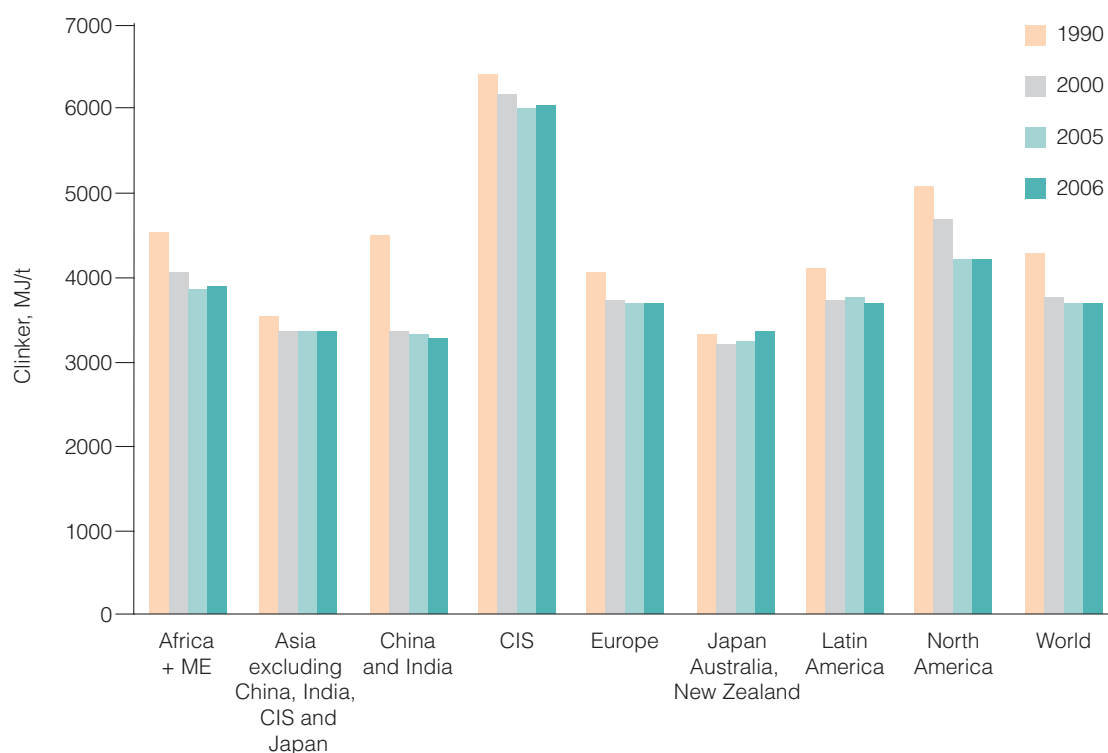

Figure 9 **Regional and global thermal efficiencies over time** (WBCSD, 2009)

process fuelled with low-priced local natural gas leading to the lowest regional thermal efficiency of clinker making (more than 6 GJ/t clinker). All kilns in Japan use energy efficient modern cement kiln technologies and therefore Japan is the world's most efficient clinker producer. It can be seen from Table 6 that there is a large number of cement kilns in operation worldwide that still use the old, inefficient technologies. This provides many opportunities to improve the regional and global average thermal efficiency of clinker production and therefore significantly reduce the CO_2 emissions in the industry.

Figure 9 shows a downward trend in the thermal energy intensity required to produce a tonne of clinker between 1990 and 2006 in most regions and globally. Cement manufacturers achieve greater energy efficiency by closing small and inefficient plants and modernising others. Market and economic forces generally trigger the closure of inefficient facilities as more advanced technologies are commissioned. The rapid economic development and demand growth for cement in many developing countries have provided an opportunity, in some cases, for developing countries to achieve relatively high levels of energy efficiency by building efficient dry-process plants to meet demand. This has been the case in China, where small-scale kilns and inefficient shaft kilns that dominated production until recently are being replaced by large, modern kilns. For example, in 1995 the output from dry kilns in China was only 6% of the total, and large- and medium-scale kilns accounted for only 33% of total output (Cui and Wang, 2006). By 2004, however, large- and medium-scale plants accounted for 63% of production and that from dry kilns around 45% of total output. This means that the energy intensity per tonne of clinker has declined from about 5.4 GJ/t clinker in 1990 to 4.5 GJ/t of linker in 2004. In 2007, the National Development and Reform Commission (NDRC) of China made a comprehensive plan that the cement produced from large-scale dry kilns should reach 80% of total production by 2010 and 95% by 2030, reducing the contribution from shaft kilns to just 5%. If this is the case, then the thermal energy intensity of clinker production in China would fall accordingly (IEA, 2007).

4.1.3   Upgrading kiln systems

While the newly-built cement plants normally use the most recently developed technologies, which are also typically the most energy efficient a significant decrease in specific energy consumption for old installations can only be achieved through major retrofits. For old cement plants, the technical equipment of cement kilns can be modernised to adapt to modern technologies.

Wet process conversion to a modern cement kiln

A wet process kiln can be converted to a modern cement kiln with a multistage preheater and pre-calciner. Studies of several kiln conversions in the USA in the 1980s found that, after the conversion, specific energy savings of 3.4 MJ/t or less were achieved (Worrell and Galitsky, 2008). Conversion of a wet kiln to a modern kiln has a high capital cost that is similar to the cost of building a new kiln. The conversion requires the demolition and reconstruction of everything in the pyroline except for half of the kiln. A new vertical raw mill is included with a new cooler. A recent study estimated that the resulting decreases in specific heat and electricity consumption would be 3308 MJ/t clinker and 15 kWh/t clinker, respectively. Power savings are the result of raw grinding efficiency improvements and the replacement of old motors with HE motors. An investment cost of $155 per annual tonne clinker capacity would be required with savings of 0.10 $/t clinker in operating and maintenance costs. The conversion could increase the production by 50% (Hollingshead and Venta, 2009). The high investment costs means that such conversion is not economically feasible under normal circumstances.

Wet process conversion to semi-wet process

Conversion of a wet process kiln to a semi-wet process kiln offers a cost effective choice for reducing thermal energy consumption and associated CO_2 emissions although the semi-wet process itself is not energy efficient compared to a modern cement kiln. The Buzzi plant at Greencastle, Indiana, USA converted its wet process to a semi-wet kiln that is equipped with a preheater and a pre-calciner. In a wet process the slurry typically contains 36% water (ranging from 24% to 48%). Adding a filter press

can reduce the moisture content to about 20%. The conversion can reduce the specific heat consumption in the kiln from 6405 MJ/t to 5660 MJ/t clinker with a 20% increase in production. The capital cost of installing filter presses and additional conveying equipment is estimated to be at $3.70 per annual tonne clinker capacity with an increased operating cost of 0.20 $/t clinker (Hollingshead and Venta, 2009). However, several US plants tried slurry filters without much success (Worrell and Galitsky, 2008).

Wet process conversion to semi-dry process

Adding a slurry dryer to dry the slurry before it enters the kiln using waste heat from the kiln can improve thermal energy efficiency and increase productivity. The dryer can be combined with a hammer mill for a reliable and efficient disagglomeration and drying system. In a cement kiln any water contained in the raw meal is evaporated by the heat. The evaporation energy needs can be halved by adding a slurry dryer, reducing thermal energy consumption by 1055 MJ/t clinker and the net energy savings are estimated at 1002 MJ/t clinker (Worrell and Galitsky, 2008).

Conversion of long dry kiln to preheater/pre-calciner kiln

Converting a long dry kiln to a rotary kiln with multistage preheaters requires a new pyroline (except perhaps for half the kiln) and minor improvements to raw grinding equipment. The conversion can reduce energy consumption by approximately 1510 MJ/t clinker with no net increase in electricity consumption. Production may increase by 25%. Investment costs are estimated at $105 per annual tonne clinker capacity with a savings of 0.10 $/t clinker in operating and maintenance costs (Hollingshead and Venta, 2009).

Converting a long dry kiln to a state-of-the-art multistage preheater and pre-calciner kiln will require more extensive upgrades in the raw grinding and clinker cooler areas to handle the increased production. The production may be increased by up to 40%. With preheaters and pre-calciner, the kiln length may be shortened by 20–30% thereby reducing heat losses through radiation (Worrell and Galitsky, 2008). The thermal energy consumption may be decreased by around 840 MJ/t clinker with no net changes in power consumption. Investment costs are estimated at $115 per annual tonne clinker capacity with savings of 0.10 $/t in operating costs (Hollingshead and Venta, 2009). The potential CO_2 emission reduction ranges from 68 to 209 kgCO_2/t cement for direct emissions, and indirect emissions reductions due to reduced consumption of electricity range from 0 to 3 kgCO_2/t cement (EPA, 2010b).

Cement manufacturing is a highly capital-intensive industry requiring large-scale equipment to be economically competitive. The high capital cost limits the financial incentive to build new plants or update old ones and so retrofits are currently limited. The increased thermal efficiencies shown in Figure 9 reflect the changing mix of kiln types across the global cement industry as older, inefficient kilns are being retired while new, more efficient kilns are built in developing countries to meet local demand. Efficiencies for individual kiln technologies have not changed substantially. In general, a major retrofit project will require that the plant has at least 50 years limestone reserves remaining for the anticipated new capacity. Another common deterrent to a major upgrade is that it will generally invalidate any exemptions of the grandfathered plant from new plant emissions standards. It is believed that a policy framework should be established to promote the adoption of best available efficiency technologies for new and retrofit kilns. A global emissions trading system would encourage companies to invest in technologies to improve energy efficiency and lower CO_2 emissions in cement production and such investments should be made financially awarding. The recent IEA's Cement Technologies Roadmap recommended several other measurers and policy support for reducing CO_2 emissions in the cement industry by 2050 (IEA/WBCSD, 2009).

4.2   Kiln system heat loss reduction

Previous studies on energy balances of dry rotary kiln systems revealed that around 40% of the total energy input into the cement kiln was being lost through hot off-gases (19.15%), cooler stack (5.61%)

and kiln shell (15.11%) (Engin and Ari, 2004). Reduction of the heat loss during the clinker production process can result in a decreased thermal consumption and therefore improved thermal efficiency. Several measure can be taken to reduce the cement kiln heat loss.

Kiln system insulation

The outer surface area of a cement kiln is very large due to the large size of the kilns. Consequently, significant heat loss can occur through the shell of a cement kiln, especially in the burning zone. Proper insulation is important to keep these losses to a minimum. The refractory material lining the kiln is the primary insulating material. The use of better insulating refractories can reduce heat losses. The refractory bricks lining the combustion zone of the kiln protect the outer steel kiln shell against heat, chemical and mechanical stresses. Although the choice of refractory materials is highly dependent on fuels, raw materials, and operating conditions, consideration should be given to refractory materials that provide the highest insulating capacity, have the longest life and the ability to develop and maintain a coating. The coating helps to reduce heat losses and to protect the burning zone refractory bricks (EPA, 2010b; Worrell and others, 2008b).

Although energy savings are difficult to quantify due to the unique conditions at each facility, some benefit may be realised from higher quality refractory materials. It has been estimated that high temperature insulating linings for the kiln may reduce fuel usage by 0.12 to 0.4 GJ/t clinker. Costs for insulation material are estimated to be $0.25 per annual tonne clinker capacity. In addition, extended lifetime of the refractories can lead to longer operating periods and reduced lost production time between relining of the kiln, and thus offsets the costs of higher quality refractories. The use of improved kiln-refractories may also lead to improved reliability of the kiln and reduced downtime, reducing production costs considerably, and reducing energy needs during start-ups (EPA, 2010b; Worrell and others, 2008a; Worrell and others, 2008b).

The investment costs for external insulation on upper preheater vessels and on the cooler housing were estimated to be 0.3 $/t clinker and to provide an energy savings of around 21 MJ/t clinker. Investment costs of 0.60 $/t clinker for improved refractory materials in the kiln and preheater may reduce energy consumption by 62.8 MJ/t cement (Hollingshead and Venta, 2009).

Kiln seals

Seals are used at the kiln inlet and outlet to reduce false air penetration, as well as heat losses. Air leakage occurs in most cement plants, especially in older plants. Leaking seals can result in increased heat loss leading to higher fuel use. Energy losses resulting from leaking seals may vary, but are generally relatively small. It has been reported that for a relatively small investment of 0.02 $/t clinker, arresting air leakage can lead to an increase in production by 3% while reducing power consumption by 3 kWh/t clinker and heat consumption by 62.8 MJ/t clinker (Hollingshead and Venta, 2009).

Improved kiln seal maintenance is generally applicable to existing facilities; however, the design of new facilities should consider the effectiveness and longevity of available kiln seals. All facilities should have a regular maintenance plan for the kiln seals to reduce leaks.

4.3   Kiln combustion system improvements

Fuel combustion systems in kilns can contribute to kiln inefficiencies. Inefficiencies are caused by incomplete fuel burning, poor mixing of fuel with combustion air, combustion with excess or inadequate air, and oversupply of coal, which can lead to higher fuel usage as well as increased NOx and CO emissions. Improved combustion systems aim to optimise the shape of the flame, the mixing of combustion air and fuel and reduce the use of excess air. Various approaches have been developed. One technique developed in the UK for flame control was reported to have resulted in fuel savings of 2% to 10% depending on the kiln type. The savings were achieved through advances in combustion technology that improve combustion through the use of better kiln control. Savings of up to 10% have

been demonstrated for the use of flame design techniques to eliminate reducing conditions in the clinkering zone of the kiln in Blue Circle cement plant (Worrell and others, 2008a).

A proprietary system called Gyro-Therm technology that improves gas flame quality while reducing NOx emissions has been demonstrated at several cement plants to improve combustion and reduce fuel usage. Originally developed at the University of Adelaide, Australia, the Gyro-Therm burner uses a patented 'precessing jet' technology. The nozzle design produces a gas jet leaving the burner in a gyroscopic-like precessing motion. This stirring action produces rapid large scale mixing in which pockets of air are engulfed within the fuel envelope without using high velocity gas or air jets. The combustion takes place in pockets within the fuel envelope under fuel rich conditions. This creates a highly luminous flame, ensuring good radiative heat transfer. Compared to conventional burner technologies, the Gyro-Therm burner requires no primary air to assist in fuel air mixing, and minimal air (3%) for burner cooling, thus reducing fuel and electricity costs (FCT, 2010). The Gyro-Therm technology can be applied to gas or gas/coal dual fuel burners. Fuel savings of 2.7% to 10% and up to a 10% increase in output of the kiln were demonstrated in cement plants in Australia and the USA. Costs for the technology vary by installation but an average cost of $0.9 per annual tonne clinker capacity was assumed based on reported costs in the demonstration projects (Worrell and others, 2008a). Payback of less than one year on average can be expected from an investment in a Gyro-Therm kiln burner (FCT, 2010).

Historically the most common firing system is the direct-fired system. Coal is dried, pulverised and classified in a continuous system, and fed directly to the kiln. This can lead to high levels of primary air (up to 40% of stoichiometric). These high levels of primary air limit the amount of secondary air introduced to the kiln from the clinker cooler. Primary air percentages vary widely, and non-optimised matching can cause severe operational problems with regard to creating reducing conditions on the kiln wall and clinker, refractory wear and reduced efficiency due to having to run at high excess air levels to ensure effective burnout of the fuel within the kiln.

In more modern cement plants, indirect-fired systems are normally applied. In these systems, neither primary air nor coal is fed directly to the kiln. All moisture from coal drying is vented to the atmosphere and the pulverised coal is transported to storage via cyclone or bag filters. Pulverised coal is then densely conveyed to the burner with a small amount of primary air. As the primary air supply is decoupled from the coal mill in multi-channel designs, lower primary air percentages are used, normally between 5% and 10%. The multi-channel arrangement also allows for a degree of flame optimisation. This is an important feature if a range of fuels is fired. Input conditions to the multi-channel burner must be optimised to secondary air and kiln aerodynamics for optimum operation. The optimisation of the combustion conditions will lead to reduced NOx emissions, better operation with varying fuel mixtures, and reduced energy losses. This technology is standard for modern plants (Worrell and others, 2008a).

Excess air infiltration is estimated to result in heat losses equal to 75 MJ/t clinker. A reduction in excess air of between 20% and 30% may lead to fuel savings of 15 to 22 MJ/t clinker. Improved combustion conditions will lead to a longer lifetime of the kiln refractories and reduced NOx emissions. These co-benefits may result in larger cost savings than the energy savings alone (Worrell and others, 2008b).

The disadvantage of an indirect firing system is the additional capital cost. In 1997, California Portland's plant in Colton, California implemented an indirect firing system for their plant, resulting in NOx emission reductions of 30% to 50%, using a mix of fuels including tyres. The investment costs of the indirect firing system were $5 million for an annual production capacity of 680,000 t clinker, or 7.4 $/t clinker (Worrell and others, 2008b). Conversion of a direct-fired system to indirect firing is estimated to be 8.40 $/t clinker in capital investment with an additional 0.05 $/t in operating costs. The benefits include a 10% production increase and energy savings of 188.4 MJ/t clinker. There is a power penalty of 0.5 kWh/t clinker for a dust collector, additional conveying blowers and high pressure fans for the new burner (Hollingshead and Venta, 2009).

4.4   Process control and management system

The operation of a kiln system under non-optimum conditions can result in heat losses and unstable process conditions leading to more operational stops. Maintaining optimum kiln operating conditions can result in more efficient operation throughout the cement manufacturing process and a reduction in total energy used. Automated computerised control systems can be used to maintain the combustion process and operating conditions in the kiln at optimum levels. The process control systems can also be used to automate the raw material weighing and blending process and control other parameters such as air and mass flow and temperature distribution in order to optimise the kiln operation. Additional process control systems include the use of online analysers that help operators to instantaneously determine the chemical composition of raw materials and the product, thereby allowing immediate changes in the blend of the materials. A uniform feed allows for a more steady kiln operation, thereby saving ultimately on fuel requirements. Process control of the kiln system can improve heat recovery, material throughput and the product quality.

Several computer control systems have been developed by different companies and most systems use so-called 'fuzzy logic' or expert control or rule-based control strategies. Instead of using a modelled process to control process conditions, expert control uses an artificial neural network to simulate the best human operator, using information from various stages in the process. These systems are now used in most modern cement plants across the world. The thermal energy savings from process control systems may vary typically between 50 and 200 MJ/t clinker and the electricity consumption may be reduced by up to 1 kWh/t clinker. The potential reduction of direct and indirect CO_2 emissions due to the energy savings is between 4 and 18 $kgCO_2$/t clinker and up to 0.7 $kgCO_2$/t clinker, respectively (ECRA/CSI, 2009). Furthermore, improving productivity and availability, increased throughput and prolonged refractory life under process controlled kiln operation have been reported (Worrell and others, 2008a). The assessment by Hollingshead and Venta (2009) showed that applying process control systems could increase production by 5% with corresponding savings of 125.6 MJ/t clinker and 7 kWh/t clinker.

There should be no barriers to installing control systems on a new construction. Most existing facilities should be able to retrofit the clinker production operations to accommodate control systems. Investment cost is assumed to be 0.95 $/t clinker with an additional 0.10 $/t clinker for operating costs (Hollingshead and Venta, 2009). Payback periods are typically two years or less (Worrell and others, 2008a).

4.5   Efficient cooler technology

The clinker cooler is an integral part of the kiln system and has a decisive influence on the performance and economy of the pyro-processing plant. Main clinker cooler technologies include rotary, planetary (or satellite), travelling and reciprocating grate coolers. For rotary and planetary coolers, the amount of cooling air is determined by the air required for fuel combustion. This leads to higher clinker end temperatures (between 120ºC and 200ºC above ambient temperature) compared with 60ºC to 80ºC above ambient temperature using grate coolers, and thereby less efficient heat recovery. The planetary cooler is not suitable for pre-calcination because tertiary heat recovery needed for pre-calciners is impossible with planetary coolers. Cooling in a grate cooler is achieved by passing a current of air upwards through a layer of clinker lying on an air-permeable grate. Two technologies are applied to transport the clinker in a grate cooler: travelling grate and reciprocating grate. The travelling grate has the same design features as the preheater grate. This design is no longer used in new installations since around 1980 due to its mechanical complexity and poor recovery resulting from limited bed thickness caused by the difficulty of achieving an effective seal between the grate and walls (EIPPCB, 2010). The introduction and development of the reciprocating grate cooler (second generation) started around 1983. In the 2000s, a new generation (the third generation of grate coolers) emerged in the cement industry. 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 modern reciprocating grate coolers are now standard technology for modern large-scale kilns.

The modern reciprocating grate coolers can have a high degree of heat recovery efficiency of 70–75% and can be operated with extended lifetimes compared with travelling grate coolers. Replacement of a planetary or a rotary cooler with a modern reciprocating grate cooler can reduce kiln fuel consumption by up to 8% but grate coolers require additional electrical power consumption of 3 to 6 kWh/t clinker. The potential reductions of CO_2 emissions due to the lower kiln fuel consumption range from 9 to 28 kgCO_2/t clinker. However, the increase in electrical power usage could result in an increase in indirect CO_2 emissions by 1 to 3 kgCO_2/t clinker (ECRA/CSI, 2009).

The cost for the conversion from a planetary cooler to the modern grate cooler with a capacity of 6000 t/d is site specific and can vary widely though it is estimated to be €15 to €20 million (ECRA/CSI, 2009). The cost of installing a completely new grate cooler is estimated to be 10 $/t clinker. A 20% increase in clinker production is expected with an additional 0.20 $/t clinker for operating cost (Hollingshead and Venta, 2009). Due to the high investment cost, grate coolers are the preferred technology for large plants and for plants with capacities smaller than 500 t/d the cost may be prohibitive. Cooler conversion may be more economically attractive if the retrofit is linked with adoption to pre-calciner technology or a significant expansion in production capacity (Worrell and Galitsky, 2008).

The old (second generation) grate cooler typically has a heat recovery efficiency of 50% to 65% but can be upgraded by adding a static inlet grate and, depending on the cooler type, a modified aeration system (ECRA/CSI, 2009). The cost of upgrading with a static inlet grate is estimated to be around 1.80 $/t clinker. The upgrade can lead to a thermal energy saving of approximately 88 MJ/t clinker and a saving of 0.10 $/t in operating costs with a corresponding 4% increase in production (Hollingshead and Venta, 2009).

4.6 Waste heat recovery for cogeneration

The temperature in cement kilns can reach 1500ºC or higher. Although some of the waste heat generated in rotary kiln may be reused to preheat raw material and to dry the raw material and the fuel, a significant quantity is lost as waste heat from exit gases. Waste gases discharged from the kiln, the clinker cooler system, and the kiln pre-heater system all contain useful energy that can be converted into power. Capture of the waste heat to generate electricity can significantly improve the overall energy efficiency of cement manufacturing.

The installation of electricity generation facilities in cement plants is not a new practice. Cogeneration systems are well established in the cement industry worldwide with Japan, China and Southeast Asian countries taking the lead in this development.

It is estimated that in dry process kilns nearly 40% of the total thermal input is discharged as waste heat from the exhaust gases of the preheater and cooler (EnergyManagerTraining, 2006). The waste heat can be reused for various applications such as drying of raw material and fuel and preheating the air required for fuel combustion in the kiln. Although modern pre-heater and pre-calciner kilns have low temperature waste heat due to the pre-heaters, there are still opportunities to produce electricity economically. The waste heat available for recovery largely depends on the kiln system used, its design and configuration. Factors influencing the amount of waste heat recoverable include the plant capacity, thermal consumption, number of stages of preheater and the type of clinker cooler. Based on the heat recovery system and the kiln technology, 7 to 8 kWh/t cement can be produced from hot air from the clinker cooler, and 8 to 10 kWh/t cement from the kiln exhaust. Total power generation can range from 7 to 20 kWh/t cement (EPA, 2010b). Table 7 gives the typical temperatures of the exhaust

Table 7   Typical temperatures of the exhaust gases from cement kiln system and the potential recoverable energy (EnergyManagerTraining, 2006)

Source of waste heat	Temperature, °C	Potential electric generation*, MWe
Pre-heater	280–415	3.0–5.5
Cooler	220–290	

*   for cement plant with capacity of 2000 – 4500 t clinker/d

Table 8   Comparison of technologies for bottom cycle power generation (Bell, 2007)

	Steam Rankine Cycle	Organic Rankine Cycle	Kalina Cycle
Waste heat temperature required, °C	>250	>200	>200
Capital cost (US$/kW generation capacity)	1100–1400	1500–3500	1100–1500
Electricity generated (Steam Rankine = 1)	1	1.3–1.7	1.3–1.6

gases from cement kiln system and the potential recoverable energy.

Cogeneration systems can either be direct gas turbines that utilise the waste heat (top cycle), or the installation of a waste heat boiler system that runs a steam turbine system (bottom cycle). The bottom cycle is more widely applied in cement plants and different technical approaches can be used for bottom cycle power generating systems. Table 8 compares the heat resource requirements, cost and possible electricity generation output of these technical approaches. The Steam Rankine Cycle has relatively low capital cost but requires a higher waste heat temperature. Having been developed and first implemented in Japan and being widely adopted in Europe and China, the steam cycle is the most common approach. The Organic Rankine Cycle (ORC), first installed in a German cement kiln, uses pentane as the motive medium which evaporates at significantly lower temperatures than water. As a result the ORC process, though more expensive, can make use of low-temperature waste heat and therefore may be more attractive to modern cement plants using dry rotary kilns with multistage preheaters and pre-calciners. The particular advantages of the ORC process are the simple operation, the compact structure and the relatively high efficiencies that can be achieved with heat sources below 275ºC (EIPPCB, 2010). Kalina Cycles have been successfully applied in industries such as steel making, but there are not yet any commercial applications in cement plants (Bell, 2007).

Top-cycle applications use waste heat or burn fuel to generate power on site, and subsequently use the exhaust heat from the generator to meet process needs. Process needs could be either needs of the cement plant such as for drying and preheating, or the needs of a neighbouring factory or community (for community heating or cooling). Aalborg Portland plant in Denmark, for example, feeds heat into a district heating network supplying approximately 15% of the municipal heat demand of the city of Aalborg (Bell, 2007).

Bottom-cycle cogeneration units offer the most environmental benefits because they use waste heat to generate electricity, so no additional fuel is burnt to generate the power. Electricity thus generated would displace that from the local grid resulting in improved overall energy efficiency, reduced energy cost and lower carbon emissions. In the case of top-cycle power plants the environmental benefits arise from increased efficiency. Today's most efficient combined cycle gas turbine (CCGT) power plants have a maximum energy efficiency of 50% to 60%. If fossil fuel is burnt to generate power in a top-cycle cogeneration system in cement plants and the waste heat is put to use for drying or preheating, the overall efficiency can reach up to 90% (Bell, 2007).

It is estimated that for a 2000 t/d (730,000 annual tonne) kiln capacity, about 20 kWh/t clinker of electricity could be generated. It has been recently reported that Chinese technology could produce 35 kWh/t clinker while Japanese technology now produces 45 kWh/t clinker. German technology is better but no data are available (Worrell and others, 2008b).

The East Africa Portland Cement Company (EAPCC) of Kenya carried out an audit of its clinker kiln to assess the possibility of cogeneration and the audit report recommended a capacity of 2.5 MW. The amount of electricity to be generated was estimated at 15 GWh per annum representing about 21 kWh/t cement. It was assumed that each MWh produced would displace 1 tCO_2 from a coal-based captive plant initially planned by EAPCC. Therefore, the CO_2 emissions reduction was evaluated at 15,000 tCO_2/y (CFA/World Bank, 2009).

Based on historic clinker production figures, it is estimated that the total potential to generate electricity using waste heat at cement plants worldwide is approximately 68.3 TWh/y or 0.41% of total global electricity demand in 2003. Even if some of the potential were realised, indirect CO_2 emissions in the cement industry could be significantly reduced. Assuming that all the electricity generated using waste heat at cement plants displaces the power that would otherwise be generated by coal combustion, then about 68.3 $MtCO_2$ emissions could be prevented every year. The total installed cogeneration capacity in the world's top twenty cement producing countries is estimated to be around 3 GW (Bell, 2007). It appears that there is significant untapped potential. Cement manufacturers who invest in cogeneration power plants have much to gain from the increased investment, the payback period is about two to three years (Worrell and others, 2008b; Sharma, 2007).

4.7   Fluidised bed cement kiln system

The rotary kiln is by far the predominant technology for clinker production worldwide. A large number of shaft kilns are also in operation in some parts of the world. Since 1986, Japan has been developing a fluidised bed cement kiln system. The system consists of a suspension preheater, a spouted bed granulating kiln, a fluidised bed sintering kiln, a fluidised bed quenching cooler and a packed bed cooler. The suspension preheater is a conventional multistage cyclone preheater that preheats the raw material. The raw material is then granulated in the granulating kiln to a specific size (1.5 to 2.5 mm diameter) at a temperature of 1300°C. The sintering of the granules takes place in the sintering kiln at a temperature of 1400°C. The clinker formed is quickly cooled from 1400°C to 1000°C in the fluidised bed quenching cooler. Finally, the clinker is cooled down to around 100ºC in the packed bed cooler (EIPPCB, 2010).

The first trials were carried out in a pilot plant with a capacity of 20 t/d between 1989 and 1995, and then in a pilot plant of 200 t/d in 1996. The cement clinker produced in the fluidised bed kiln is the same as or better quality than the clinker from a commercial plant. A feasibility study of a 3000 t/d clinker plant showed that using a fluidised bed kiln system may reduce thermal energy consumption by 10% to 12% compared with a suspension preheater rotary kiln with grate cooler. This may lead to a reduction in CO_2 emissions by 10% to 12% (EIPPCB, 2010).

Based on the results from the 200 t/d pilot plant tests, another study estimated that a fluidised bed kiln could reduce thermal energy consumption by up to 300 MJ/t clinker, leading to a reduction in direct CO_2 emissions of up to 27 $kgCO_2$/t. However, the fluidised bed kiln has higher electricity use (increase of 9 kWh/t) resulting in a rise in indirect CO_2 emissions by 4 to 6 $kgCO_2$/t clinker (ECRA/CSI, 2009).

It should be noted that this technology is not yet available commercially for the cement industry and it may be difficult to scale up the experiences to above 5000 t/d clinker capacity.

5   Electrical energy efficiency

The cement industry consumes around 1.5% of total electricity produced globally (WWF, 2008). Most of the electricity is generated by combustion of fossil fuels leading to CO_2 emissions. The electricity consumption for cement production ranges from 90 to 150 kWh/t cement (EIPPCB, 2010). The main users of electricity are the (raw and finishing) grinding processes and the kiln line. For a cement plant using a dry process, the power consumption can be assigned to approximately 5% for raw material extraction and blending, 24% for raw material grinding, 6% for raw material homogenisation, 22% for clinker production including solid fuel grinding, 38% for cement grinding and 5% for conveying, packing and loading (ECRA/CSI, 2009). As grinding processes consume most of the power, grinding technologies have a major impact on total electric energy demand. Cement performance also has an important impact on power consumption. For example, the higher strength a cement has, the finer it has to be ground, the higher the power consumption required. On the other hand, measures that increase thermal efficiency in many cases have higher electricity usage. Electricity usage accounts for 25% to 30% of the cement production cost which is a strong incentive to keeping its consumption low (WWF, 2008).

5.1   Advanced grinding technologies

5.1.1 Raw and finishing grinding

Grinding processes require more than 60% of the electric energy demand for cement production. For a dry process, the grinding systems commonly used are ball mill, vertical roller mill, horizontal roller mill and roller presses. A ball mill is relatively easy to operate under stable operating conditions and has a high operating reliability and availability. However, ball mills have a higher specific energy consumption and are the least energy efficient compared with the other mill types (EIPPCB, 2010). Vertical roller mills (VRM) use two to four grinding rollers that are supported on hinged arms and ride on a horizontal grinding table or grinding bowl. VRM can handle mill feeds with relatively high moisture contents and are therefore suited to simultaneous grinding and drying. High pressure twin roller mills need a comparatively high degree of maintenance and they are often used in conjunction with ball mills. A more recent development is the horizontal roller mill which consists of a short horizontal shell supported on hydrodynamic or hydrostatic bearings. The shell is rotated via a girth gear. Inside the shell is a horizontal roller that is free to rotate and can be pressed hydraulically onto the shell. There are only a few horizontal roller mills in operation (EIPPCB, 2010). The key characteristics and related energy consumption of some grinding techniques are compared in Table 9.

Table 9	Comparison of grinding techniques (EIPPCB, 2010)			
Grinding process	Energy consumption, %	Maintenance requirement	Drying capacity	Suitability for grinding to great fineness
Ball mill	100	minor	average	good
Gutbett roller mill	65–50	minor to major	low*	average
Vertical roller mill	75–70%	average	high	average
* drying in classifier				

Most older facilities still use ball mills for grinding and they account for almost 60% of all mills in cement plants (ECRA/CSI, 2009). A significant reduction of specific energy demand for grinding processes can be achieved either by combining the existing ball mills with vertical/horizontal roller mills or high pressure roller presses, or by replacing ball

mills with high-efficiency roller mills. The use of these advanced mills saves energy without compromising product quality. Replacing older ball mills with VRM or high pressure roller mills can reduce the electricity demand of the grinding operation from 12 to 16 kWh/t cement, which may reduce indirect CO_2 emissions by 7 to 11 kgCO_2/t cement (ECRA/CSI, 2009). Another study found that the investment costs for converting ball mills to VRM for raw grinding would be 39 \$/t clinker while saving 0.20 \$/t in operating costs. Power savings due to the conversion were estimated at 9.9 kWh/t clinker. A 10% higher investment cost, 42 \$/t clinker, would be required to convert ball mills to VRM for cement grinding due to finer product requirements with a more difficult grindability. An operating cost penalty of 0.20 \$/t was assumed for more frequent maintenance activities. Power savings were estimated at 11 kWh/t clinker (Hollingshead and Venta, 2009).

Using roller presses for pre-grinding in combination with ball mills can also result in a significant reduction in power consumption. Minor changes will be required to retrofit a roller press to an existing ball mill system. Capital cost of the retrofit vary widely from \$2.3 to \$7.3 per annual tonne cement capacity with estimated power savings of 6 to 22 kWh/t cement (Worrell and Galitsky, 2008). A recent study estimated the overall cost of installing a new roller press to be 6.50 \$/t with additional operating costs of 0.08 \$/t clinker. The estimated power savings are 9 kWh/t clinker (Hollingshead and Venta, 2009).

The Horomill, a type of horizontal roller mill, 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 21 kWh/t and even for pozzolanic cement with a Blaine of 4000, power use may be as low as 25 kWh/t cement (Worrell and Galitsky, 2008). The cost for converting a ball mill to a Horomill or roller press in a closed circuit with a high efficiency classifier is estimated at 20 \$/t clinker and additional operating costs of 0.10 \$/t clinker. Power savings of 13 kWh/t clinker are associated with the upgrade (Hollingshead and Venta, 2009).

In most wet process kilns, tube mills are used in combination with closed or open circuit classifiers. An efficient tube mill system consumes about 13 kWh/t. Replacing the tube mill by a wash mill with closed circuit classifier would reduce electricity consumption for raw grinding to 5 to7 kWh/t, or by 40% to 60%. When replacing a tube mill a wash mill should be considered as an alternative. The investment and operating costs of a wash mill are comparable to a tube mill system (Worrell and Galitsky, 2008).

5.1.2   Fuel preparation

Coal is the most widely used fuel in the cement industry and most often fuel preparation (crushing, grinding and drying) is carried out on site. The three main types of coal milling and grinding processes that are commonly used are tube mill, vertical roller or ring-ball mill and impact mill. As discussed above, roller mills are typically more efficient than other grinding methods. For coal operation, the electricity consumption of a vertical roller mill is estimated at 16 to 18 kWh/t of coal, compared with 25 to 256 kWh/t for a tube mill and 45 to 60 kWh/t for an impact mill. The investment costs for a roller mill are higher than those of the other two methods, but the operating costs are lower; roughly 20% lower than a tube mill and over 50% lower than an impact mill with estimated savings at 7 to 10 kWh/t of coal (Worrell and Galitsky, 2008).

Roller presses, like those used for raw material and cement grinding, are generally more efficient than conventional grinding mills. Roller presses can be used to grind raw materials and coal interchangeably, although coal-grinding equipment needs special protection against explosions (Worrell and Galitsky, 2008).

5.1.3 Optimisation of mill operation

Operating grinding mills at optimum conditions can potentially save energy. Parameters that hold potential energy savings include load level, revolution speed, combination of the ball charge, lining design and the adjustments of the separator. Computerised control systems for grinding operations optimisation have been developed using the same approaches as for cement kilns (*see* Section 4.4). These systems have been implemented in a number of cement plants. Power savings of 2.5% to 10% with production increases of 3% to 10% have been reported. The product quality also has been improved after installing the control systems. The payback period is estimated to be 1.5–2 years (Worrell and Galitsky, 2008).

5.1.4 Improved grinding media

Grinding media are usually selected according to the wear characteristics of the material. Increases in the ball charge distribution and surface hardness of grinding media and wear resistant mill linings have shown a potential for reducing wear as well as energy consumption. Over the years, the material and design of the rollers have been improved and optimised. Installing an optimised ball charge is estimated at 0.21 $/t clinker and should provide a 3% production increase with power savings of 1.8 kWh/t clinker for cement grinding with a ball mill.Upgrading balls, liners and diaphragm in a ball mill is estimated to cost 2.65 $/t clinker with an expected 3% production increase. The potential reduction in grinding energy use is estimated to be 5% to 10% in some mills, which is equivalent to power savings of 1.8 kWh/t clinker (Worrell and Galitsky, 2008; Hollingshead and Venta, 2009). Other improvements include the use of improved liner designs, such as grooved classifying liners. These have the potential to reduce grinding energy use by 5% to 10% in some mills, which is equivalent to estimated power savings of 3 to 5 kWh/t cement (Worrell and others, 2008b).

5.2   Raw material blending/homogenising

The raw material consists of a number of ingredients. To produce a good quality product and to maintain optimal and efficient operating conditions in the kiln, the raw meal must be mixed thoroughly to form a homogenous mixture. For dry process kilns, the mixing/blending may be carried out in an air-fluidised silo using compressed air to agitate the powdered meal, or using a mechanical system that simultaneously withdraws material from several storage silos. The energy consumption ranges from 1 to 1.4 kWh/t of raw meal for an air-fluidised homogenising silo and 2 to 2.4 kWh/t for a mechanical system. Air-fluidised homogenising silos have good blending efficiency and relatively low energy consumption and hence are used in most cement plants whilst the less efficient mechanical systems are still in operation in some older plants (Worrell and Galitsky, 2008). In modern cement plants, gravity-type homogenising silos (or continuous blending and storage silos) are used in which the raw material funnels down one of many discharge points, where it is mixed in an inverted cone. Although gravity-type silos may not give the same blending efficiency as air-fluidised systems, gravity-type silos appear to be most commonly used in new plants because of the significant reduction in power consumption. The gravity-type silos may reduce energy consumption by 0.9 to 2.3 kWh/t of raw meal. Silo retrofit costs are estimated to be 5.0 $/t cement, or $3.3/t raw material (assuming capital cost of $550,000 per silo with an average capacity of 150,000 t/y) (Worrell and Galitsky, 2008; EPA, 2010b). Rather than constructing entirely new silo systems, modifications at existing facilities may be cost effective when the silo can be partitioned with air slides and divided into compartments which are sequentially agitated (Worrell and Galitsky, 2008).

Hollingshead and Venta (2009) estimated that improvements in raw meal mixing/blending systems could reduce the specific heat consumption in the kiln by around 21 MJ/t clinker and the power consumption by 1.2 kWh/t while increasing production by 5%. Investment costs were estimated to be 3 $/t clinker and operating costs would increase by 0.02 $/t clinker.

5.3   High efficiency classifier/separator

After grinding, classifiers/separators are used to separate particles by size, with the larger particles being returned to the grinder for further processing. Classifiers that have lower efficiencies return some smaller particles back to the grinder that should have been allowed to pass to the next operation, resulting in extra power use in the grinding mill. A recent development in efficient grinding technologies is the application of high efficiency classifier/separators which feature optimised air ducts and additional external air circuits. The high separation efficiency means a higher proportion of classifier fines, leading to a reduced number of circulations of the mill feed and an increase in throughput by up to 15% (ECRA/CSI, 2009). Energy savings through implementing high efficiency classifiers are estimated to be 8% of the electricity usage of the grinder. It has been reported that replacing a conventional classifier by a high efficiency classifier resulted in a 15% increase in the grinding mill capacity and improved product quality due to a more uniform particle size, both in raw meal and cement. The better size distribution of the raw meal may lead to fuel savings in the kiln and improved clinker quality (Worrell and Galitsky, 2008).

A recent study estimates that the investment cost of replacing a conventional classifier with a high efficiency classifier (including a product dust collector and new fan) is 2 $/t clinker with 0.05 $/t additional operating cost. The retrofit may lead to power savings of 2.5 kWh/t clinker and a 10% production increase (Hollingshead and Venta, 2009). Another study estimates that the decrease in electricity use as a result of installing a high efficiency classifier/separator is 4 kWh/t cement, which may lead to CO_2 emission reductions of 2 to 3 kgCO_2/t cement. The investment costs of installing high efficiency classifiers/separators at a new plant or retrofitting an existing facility with 2 Mt/y clinker capacity are about €2.5 million, with an operating cost decrease of about 0.28 €/t cement (ECRA/CSI, 2009).

5.4   Efficient transport systems

Transport systems are required to convey materials such as kiln feed, kiln dust, finished cement and fuel throughout the plant. Pneumatic and mechanical conveyor systems are usually used to transport the materials. Mechanical conveyors use less power than pneumatic systems. Replacing pneumatic systems with mechanical belt conveyors and bucket elevators are among the least expensive options for bulk material transport in a cement plant with estimated investment costs at 4.10 $/t clinker (3.43 $/t cement) and a reduction in operating costs of 0.20 $/t clinker (0.17 $/t cement). The resulting power savings are expected to be 3.0 kWh/t clinker (Hollingshead and Venta, 2009; EPA, 2010b). In another recent study, it is estimated that switching from pneumatic to mechanical conveyor systems can save 2.9 kWh/t cement with installation costs of 4.1 $/t cement (EPA, 2010b). For existing facilities, the conversion from pneumatic systems to mechanical systems may be cost effective due to increased reliability and reduced downtime (Worrell and Galitsky, 2008).

5.5   High efficiency motors and drives

Motors and drives are used to drive fans, rotate the kiln, transport the materials, for air compressors and, most importantly, for grinding. Motors and drives are the main power consumer in the cement production process. Therefore, improving the efficiency of motor systems can result in a significant reduction in electricity use leading to lower indirect CO_2 emissions.

5.5.1 A system approach

Between 500 and 700 electric motors with varying electrical capacities may be used in a cement plant (ECRA/CSI, 2009). Due to the high number of motors at a cement manufacturing facility, it is

important to take a systems approach when considering energy efficiency improvements to the motor systems. Such an approach strives to optimise the energy efficiency of entire motor systems rather than that of motors as individual components. An evaluation of energy supply and energy demand may be performed to optimise overall performance. A system approach takes the following factors into consideration (EPA, 2010b):

- strategic motor selection;
- maintenance;
- proper size;
- adjustable speed drives;
- power factor correction;
- minimise voltage imbalance.

Strategic motor selection

The selection of energy efficient motors can be an important strategy for reducing power consumption as well as motor system life-cycle costs for up to 95% of a motor's costs can be attributed to the energy it consumes over its lifetime, while only around 5% of a motor's costs are typically attributed to its purchase, installation, and maintenance. In general, replacing existing motors with high efficiency motors is most economically attractive when annual operation of the motors exceeds 2000 hours (Worrell and Galitsky, 2008). Replacing the existing older, less efficient motors on the blowers and pumping systems with new, high efficiency motors (95%) at a cement plant recently resulted in a reduction in electricity use by about 2.1 million kWh/y and saved about 168,000 $/y in energy costs and 30,000 $/y in maintenance costs (VDZ and PENT, 2008).

The capital cost of replacing all older motors with high efficiency motors is estimated to be 0.80 $/t clinker with no additional operating costs and power savings of about 5%, or 5 kWh/t clinker (Hollingshead and Venta, 2009).

Maintenance

Effective motor maintenance can prolong motor life and reduce the power consumption of the motors. The purpose of motor maintenance is also to predict a motor failure and to prevent unexpected downtime of motors. The savings associated with an ongoing motor maintenance programme could range from 2% to 30% of total motor system energy use (Worrell and Galitsky, 2008).

Proper size

Motors that are sized inappropriately result in unnecessary energy losses. Replacing oversized motors with properly sized motors saves, on average for US industry, 1.2% of total motor system electricity consumption. Higher savings can often be realised for smaller motors and individual motor systems (Worrell and Galitsky, 2008).

Adjustable speed drives

In cement plants large variations in load occur. Adjustable or variable speed drives better match speed to load requirements for motor operations, and therefore ensure that motor energy use is optimised to a given application. Adjustable speed drive systems are 'off-the-shelf' technology and are available worldwide. The power savings depend on the flow pattern and loads, and may vary considerably between 7% and 60% (Worrell and Galitsky, 2008), or from 3 to 9 kWh/t cement (ECRA/CSI, 2009). This may lead to a reduction of indirect CO_2 emissions of 1 to 5 kgCO_2/t cement (ECRA/CSI, 2009). The cost of retrofitting is highly site-specific, but may range from $0.38 to $0.53 million. Operational savings from reduced electricity usage may range from 0.41 to 0.96 $/t cement (EPA, 2010b). In many cases, power savings will pay for the purchase and installation of a adjustable speed drive in less than three years (VDZ and PENT, 2008).

In a cement plant, adjustable speed drives are mainly applied for fans in the kiln, cooler, preheater, separator and mills, and for various drives. There are several methods to control airflow rates in fans. Dampers are a common method used to control fans' airflow, but the efficiency of a fan and its motor

is significantly reduced when a damper operates at partial load. Replacing the damper on the kiln fan system with adjustable speed drives can reduce energy consumption and maintenance costs. The use of adjustable speed drives for a kiln fan at one cement facility resulted in improved operation, reliability and a reduction in electricity consumption by nearly 40% of the 750 kW fan motor. Another facility which replaced their kiln ID fans with adjustable speed drives saw a reduction in electricity use by 5.5 kWh/t cement (6.1 kWh/t clinker). A Chinese company, operating ten cement plants, installed variable speed drives in 40 large motors (over 55 kW) and over 40 of its smaller motors (<55 kW) and found energy savings of over 30% (Worrell and others, 2008b). Installing adjustable speed drives for the kiln fan is applicable to both new and existing facilities.

A good application of adjustable speed drives is also found with clinker cooler fans. Investment costs of installing adjustable speed drives for clinker cooler fans are estimated to be about 0.80 $/t clinker and power savings of 7 kWh/t are expected (Hollingshead and Venta, 2009).

Power factor correction

Inductive loads such as transformers and electric motors may cause a low power factor resulting in increased power consumption, and hence increased electricity costs. The power factor can be corrected by turning off idle electric motors, replacing motors with high efficiency motors, and installing capacitors in the AC circuit to reduce the magnitude of reactive power in the system (Worrell and Galitsky, 2008).

Minimise voltage imbalance

Voltage imbalances degrade the performance, reduce motor efficiency and shortens the life of motors. For a 75 kW motor operating 8000 h/y, a correction of the voltage imbalances from 2.5% to 1% will result in electricity savings of 9500 kWh or almost $500 at an electricity rate of 0.05 $/kWh. The voltages should be monitored regularly at the motor terminal and through regular thermographic inspections of motors to identify any voltage imbalances and the voltage imbalances can be minimised by using electric voltage regulators/controllers (Worrell and Galitsky, 2008).

5.5.2   Kiln drive

A substantial amount of power is used to rotate the kiln due to its large size. When direct current (DC) motors are used, the highest efficiencies are achieved using a single pinion drive with an air clutch and a synchronous motor. The system may reduce kiln drive electricity use by 2% to 3%, which is equivalent to 0.5 kWh/t clinker at slightly higher capital costs of 6% (Worrell and Galitsky, 2008).

More recently, the use of alternative current (AC) motors is advocated to replace the traditionally used DC drive. The use of AC motor system may result in slightly higher efficiencies leading to 0.5% to 1% reduction in electricity use of the kiln drive and has lower investment costs. Using high-efficiency motors to replace older motors may result in power savings of 0.55 to 3.9 kWh/t, which equates to a reduction of 2% to 8% in power costs for the kiln drive. This amounts to a reduction in indirect CO_2 emissions of 0.48 to 3.3 kgCO_2/t clinker (Worrell and others, 2008b).

5.6   Low pressure drop cyclones for suspension preheaters

Cyclones are used to preheat the raw meal prior to the kiln using the waste heat of exhaust gases from the kiln or clinker cooler. The large pressure drop losses in the cyclones mean higher electricity consumption of the kiln or clinker cooler exhaust fans. State-of-the-art cyclones with low pressure drop reduce the power consumption of the exhaust gas fan system. One study estimated that, depending on the efficiency of the fan, energy savings of 0.6 to 0.7 kWh/t clinker can be achieved for each 490 Pa the pressure loss is reduced (Worrell and Galitsky, 2008). For most older kilns this amounts to savings of 0.6 to 1.5 kWh/t clinker (ECRA/CSI, 2009).

Retrofit of the low pressure drop cyclones can be expensive since it often requires the rebuilding or the modification of the preheater tower, and the costs are very site specific. In addition, new cyclone systems may increase overall dust loading and increase dust carryover from the preheater tower. However, if an inline raw mill follows it, the dust carryover problem becomes less of an issue. Investment costs are estimated to be $2.7 per annual tonne clinker capacity (Worrell and Galitsky, 2008). A recent assessment by Hollingshead and Venta (2009) estimated that the investment cost for this option, based on replacing the inlet and outlet cyclone ducting, is 3.50 $/t clinker with power savings of 3 kWh/t and a production increase of 3%. The resulting reduction in indirect CO_2 emissions is estimated to be up to 1 kgCO_2/t clinker (ECRA/CSI, 2009).

5.7   High efficiency fans

Fan technology has improved greatly since many older plants were constructed. Today, fan efficiencies can approach 80% while many older fans operate at efficiencies ranging from 60% to 75%. Replacing low efficiency fans with high efficiency models may reduce power consumption by 1.0 kWh/t clinker. Investment costs are estimated at 0.50 $/t clinker (Hollingshead and Venta, 2009).

5.8   Slip power recovery system

A fluid drive for kiln ID fan control is relatively inefficient and can be replaced with a slip power recovery system. A slip power recovery configuration provides an attractive alternative for adjustable speed drives and generating systems due to its improved efficiency and low power converter rating. Replacing the existing fluid drive with a slip power recovery system for kiln ID fan control may result in power savings of 0.62 kWh/t clinker. The investment costs are estimated to be about 0.25 $/t clinker (Hollingshead and Venta, 2009).

5.9   Comments

The cement manufacturing process is highly energy intensive and hence, a primary option to reduce CO_2 emissions in cement production is to improve energy efficiency. Although technical changes in production processes and equipment can help to reduce energy use, enhance productivity and lower CO_2 emissions, there are several other measures that can be taken to improve energy efficiency and reduce CO_2 emissions. These measures do not involve implementing advanced technologies and they include plant wide energy management, preventative maintenance and staff training.

Energy management
Changing how energy is managed by implementing a plant-wide energy management programme is one of the most successful and cost-effective ways to bring about energy efficiency improvements. An energy management programme should establish assessment, planning and evaluation procedures to achieve and sustain the potential energy efficiency gains of new technologies or operational changes. First, cement plants use energy for equipment such as motors, pumps and compressors and these components require regular maintenance, optimised operation and replacement when necessary. Therefore, a critical element of plant energy management involves the efficient control of crosscutting equipment that powers the production process of a plant. Second, process optimisation and ensuring the most efficient technology is in place is a key to realising energy savings in a plant's operation. And finally, throughout a plant, there are many processes operating simultaneously and fine-tuning their efficiency can produce energy savings (EPA, 2010b; Worrell and Galitsky, 2008).

Preventative maintenance
Preventative maintenance can be extremely valuable to identify maintenance issues so that cost-effective repairs can be conducted instead of catastrophic, emergency repairs. Preventative

maintenance includes training personnel to be attentive to energy consumption and efficiency. It can also provide bearing monitoring and improved lubrication schedules which will result in lower friction factors and lower power consumption. In addition, preventative maintenance can increase a plant's utilisation ratio, since it has less downtime over the long term. Preventative maintenance may result in thermal and electrical energy savings of 25 MJ/t and 3 kWh/t clinker, respectively. The capital costs are estimated to be 0.05 $/t and the operating costs are expected to increase by 0.05 $/t clinker. An increase in production by 1% is also achieved due to less downtime (Hollingshead and Venta, 2009).

Staff training

Although implementing advanced technologies can significantly improving a plant's energy efficiencies, changes in staff behaviour and attitude can also have a great impact. A knowledgeable workforce is more likely to have a higher productivity rating than a less well trained workforce. Energy efficiency training programmes can help a plant's operators incorporate energy efficiency practices into their day-to-day work routines. Trained workers can also identify inefficiencies much more quickly and make better repairs when required. Though changes in staff behaviour (such as switching off lights or closing windows and doors) often save only small amounts of energy at one time, taken continuously over longer periods they can have a much greater effect than more costly technological improvements. A training investment of 0.05 $/t can result in a 1% production increase, and a reduction in thermal and electrical energy consumption by 21 MJ/t and 0.5 kWh/t clinker, respectively (Hollingshead and Venta, 2009; Worrell and Galitsky, 2008).

Cement manufacturing involves complex processes and a large amount of equipment. Energy efficiency improvements can be achieved through several approaches such as implementing best available technologies and non-technical measures as discussed above. There is a large number of technologies and measures available to improve thermal and electrical energy efficiencies at a cement plant and therefore reduce CO_2 emissions. While many of the available technologies and measures are discussed here, this report does not necessarily represent all potentially available technologies or measures that may be applied to cement plants. The technologies and measures discussed here are those considered to have the potential to achieve or to contribute to a high level of energy efficiency improvements, or the most cost effective methods for lowering CO_2 emissions. Other opportunities exist for reducing CO_2 emissions in the cement industry and they will be discussed in the following chapters.

6 Alternative fuels

Table 10	Comparison of fuel prices, heating values and related CO_2 emissions (WWF, 2008)	
Fuel type	Energy content, GJ/t	Price, $/GJ (2010 forecast)
Coal	29	1.9 (± 20%)
Heavy oil	69	7.8 (± 5%)
Natural gas	51.5	7.6 (± 5%)

The most widely used fuels in the cement industry are coal, petroleum coke (petcoke) or heavy oils. These conventional fuels are carbon intensive. Natural gas is also used for firing cement kilns. Fuel consumption typically accounts for around 30% of the cement production costs and hence fuel price is of paramount importance in the choice of fuel. Table 10 compares the cost and energy content of fossil fuels. Despite the fact that coal is the most carbon-intensive fossil fuel, it is still the dominant fuel used for the cement industry in many areas of the world due to its relatively low price. As discussed in Chapter 3, approximately 40% of the CO_2 released during cement manufacturing is the result of fossil fuel combustion in the kiln. Considering the volume of the global cement production, switching from high carbon-intensive fuels to less carbon-intensive fuels or replacing the conventional fuels with alternative fuels such as biomass and waste derived fuels may result in a significant reduction in CO_2 emissions.

The CO_2 emissions reduction potential of replacing conventional fuels with alternative fuels depends on the CO_2 emission factors related to the energy content of the alternative fuels compared with that of conventional fuels, and the substitution ratio. Typical alternative fuels used by the cement industry include:

- discarded tyres;
- plastics, textiles and paper residues;
- pre-treated industrial and municipal solid wastes (domestic waste);
- waste oil and solvents;
- biomass.

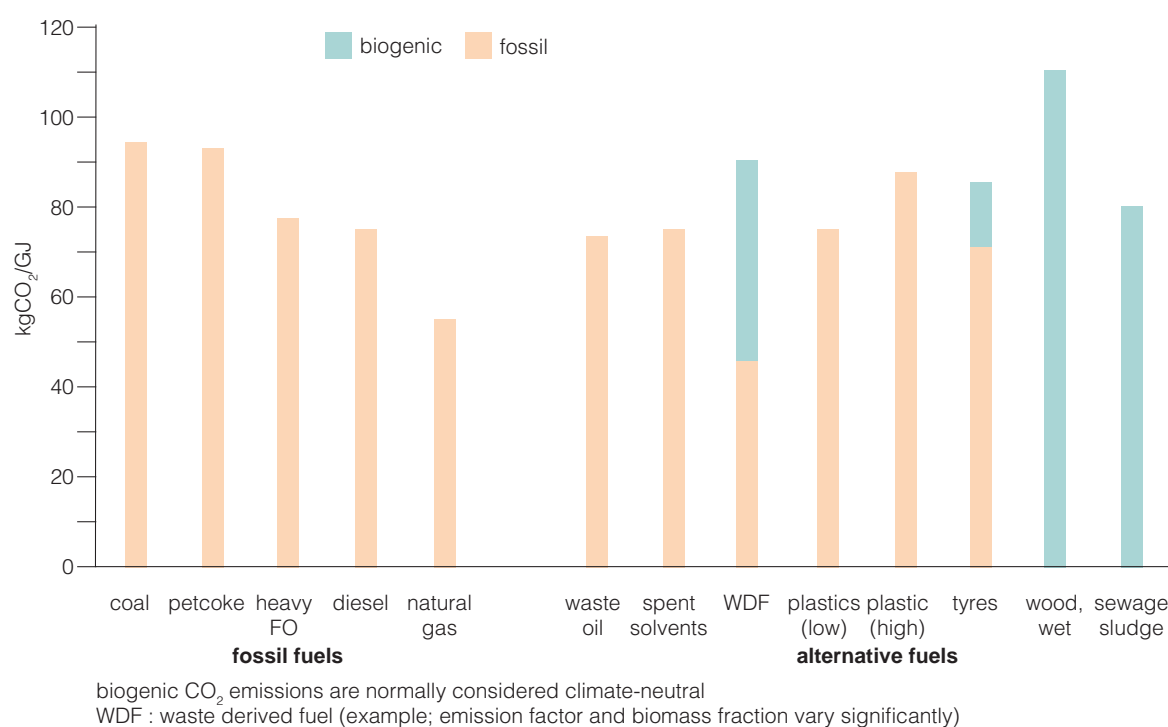biogenic CO_2 emissions are normally considered climate-neutral
WDF : waste derived fuel (example; emission factor and biomass fraction vary significantly)

Figure 10 Comparison of the typical CO_2 emission factor of different fuels (Roeder, 2010)

Figure 10 compares the CO_2 emission factor of different fuels. The CO_2 emissions from biomass fuels are accounted as zero, and most waste fossil fuels and some of alternative fuels have lower CO_2 emission factors than coal or petcoke so they can be effective substitutes with lower CO_2 emissions than conventional solid fuels. In some cases, using alternative fuels may not lead to a reduction and may even result in an increase in the CO_2 emissions in the cement production. The overall CO_2 emissions, however, are decreased from the use of alternative fuels because: 1) if these materials would otherwise be considered as waste and incinerated, additional fossil fuels would be needed in the incineration process, themselves emitting CO_2, and 2) waste materials having a considerable heat content used to substitute fossil fuels save energy and natural resources.

The potential achievable worldwide to replace conventional fuel with alterative fuels was evaluated to be 12%, and it was estimated that the use of alternative fuels could lead to a reduction in CO_2 emissions from the cement sector by 160 Mt/y in 2030 (WWF, 2008).

6.1 Switching to lower carbon fossil fuels

Like the power generation sector and many other industries, one way that the cement industry may choose to reduce its net emissions of CO_2 is to switch from high carbon content fuels to low carbon content fuels. Natural gas features a considerably lower CO_2 emission factor. The effect of switching from coal or petcoke to natural gas on CO_2 emissions reductions is more significant than the effect of increased alternative fuel use, of energy efficiency improvements or of clinker substitution (*see* Chapter 7). From the data shown in Figure 10 one can see that switching from coal to natural gas may lead to a reduction of CO_2 emissions related to energy content of the fuels by approximately 41.7%. The CO_2 emissions reduction potential of switching from lignite (emission factor of around 98 $kgCO_2$/GJ) to natural gas is even higher (ECRA/CSI, 2009). Switching from coal to heavy oil may also result in a reduction of fuel energy content related CO_2 emissions by almost 17.7%. The use of natural gas to fire cement kilns can be seen in Russia, the Middle East, Africa and Latin America.

As mentioned above, the choice of cement kiln fuel is predominantly influenced by the cost of the fuel. The availability and security of the fuel supply are also important factors on fuel selection. In most regions of the world, the main barrier to switching from coal or petcoke to oil and/or natural gas is the higher price of the latter. Due to the significantly lower price of coal compared with oil or gas, it is often not economically viable to switch from coal to oil or natural gas even when financial incentives (carbon credit, its future price is assumed to range from 20 to 30 $/t$CO_2$) have been taken into account. Cement plants use mainly cheaper, lower grade coals with higher ash content and lower heating values. The coal ash becomes part of the product bringing additional benefit to the operator. As well as the fuel cost, extra costs may arise from a fuel switch if the transport facility or gas pipeline is not already available. Also, in cement kilns the switch from coal to natural gas does not bring any efficiency gain as it does in the power sector.

6.2 Biomass fuels

As opposed to fossil fuels, biomass is renewable and the CO_2 generated from burning biomass is considered climate-neutral because an equivalent quantity of CO_2 has been absorbed by the biomass during its growth. Cement kilns are well suited to burn various types of biomass and waste derived fuels because they operate at a flame temperature exceeding 2000ºC with long residence times (approximately 6 seconds under flame temperature) and under conditions characterised by high turbulence and an oxidising environment which are ideally suited for complete combustion of nearly any flammable material.

Some commonly available biomass that can be used as cement kiln fuel include:
- agricultural residues such as rice husk;

- animal meal, animal fat;
- biomass crops;
- wood, wood waste;
- paper, pulp and paper residue;
- sewage sludge.

Replacing fossil fuel with biomass saves energy and natural resources as well as reduces CO_2 emissions. The ENCI Maastricht cement plant in the Netherlands started to burn biomass in its cement kilns in 1997. The share of biomass in the kiln fuel was 44% in 2007, which resulted in a reduction in CO_2 emissions by 28% compared to the 1990 levels (Junginger and van Dam, 2009).

The Clean Development Mechanism (CDM), defined in Article 12 of the Kyoto Protocol, provides the opportunity for developed countries to invest in GHG emission reduction projects in developing countries. Such projects can earn saleable certified emission reduction (CER) credits based on approved CDM methodologies, each equivalent to one tonne of CO_2, which can be counted towards

Figure 11 Impact of the alternative fuels use on overall CO_2 emissions (Roeder, 2010)

meeting Kyoto targets. The PT Indocement of Indonesia registered such a CDM project for CO_2 emissions reduction through partial substitution of fossil fuels with alternative fuels in three of its twelve cement plants. The three plants are Citeureup, Cirebon and Tarjun each having an annual production capacity of 10.4, 2.4 and 2.4 Mt clinker respectively. The project aims to contribute up to about 15% of Indocement's total heat requirements from biomass and other alternative fuels. The CO_2 emission reductions from this project are due to biomass fuels which are regarded as CO_2-neutral. The O_2 emissions from alternative fuels which are not bio-fuels are included in the project emissions. The CER from this project for the period of 1 November 2006 to 31 July 2007 were calculated to be 68.81 ktCO$_2$ (http://cdm.unfccc.int). The proposed Senegal's SOCOCIM CDM project aimed to replace 40% coal with Jatropha fruits and biomass residues for combustion in the cement kiln. The installed clinker production capacity of the plant is 1.35 Mt/y. It was estimated that at full implementation, about 96,000 t of biomass would be required annually for the kiln operation, and the CER would be about 0.162 MtCO$_2$/y (CFA/World Bank, 2009).

The use of biomass also allows recovery of a higher resource value from wasted materials which may otherwise be disposed to landfill, burnt in the open with no energy recovery or left to slowly decompose in the open. Therefore, the use of biomass in some instances can contribute to saving landfill space, avoiding emissions associated with uncontrolled burning and avoiding any methane generation from slow anaerobic decomposition (see Figure 11). However, use of biomass presents several challenges.

6.2.1 Technical challenges

Table 11	Energy content of biomass fuels compared with coal (WWF, 2008; Warnken and Giurco, 2003)
Material	Energy content, MJ/kg
Coal	29
Straw	15
Wood	11–20
Rapeseed	25
Corn	15
Rise hulls	12–13
Wheat residues	15
Grape marc	10–16
Coconut husk	14
Cow dung	11
Tallow	38
Vegetable oil	40
Dried sewerage sludge	9–13

Principally, the conventional fossil fuel use in cement kilns can be substituted up to 100% by alternative fuels. Nevertheless, there are certain technical barriers that limit the uptake of biomass as an alternative fuel source. Biomass based fuels are from very diverse origins and therefore the fuel quality is highly variable, both in terms of heating value and composition. For example, dried sewage sludge is high in ash and nitrogen content, whereas agricultural based bio-fuels generally contain higher percentages of nitrogen and chlorine. The mercury and chlorine contents of some biomass fuels and the impact of the sludge's P_2O_5 on early strength levels of the resultant cement product limits biomass fuel utilisation.

One of the most important technical criteria in selecting biomass fuels for a cement kiln is the heat content they provide. Biomass typically has a high moisture content and low heating value. For example, green wood is difficult to burn because its moisture content may exceed 60%. The biomass fuel burned at the ENCI Maastricht cement plant in the Netherlands consists of mainly sewage sludge that has a moisture content of 75% and a heating value of only 1.5 to 2 GJ/t. In many cases, biomass and other waste derived fuels need to be pre-treated before being used as fuel. In the case of the ENCI Maastricht plant, sewage sludge is dried before being transported to the site where it is ground to required sizes and burned in the kiln. In dry form the sewage sludge has a moisture content of 10% to 15% and a heating value of approximately 12 GJ/t (Junginger and van Dam, 2009). Typical heating values of different biomass fuels are shown in Table 11. It can be seen from Table 11

that the heating values of biomass fuels vary widely but on average they are about half that of coal. Due to the high temperature required for clinker production, the fuels used for main firing of a cement kiln should have a heat content of at least 20 to 22 GJ/t of fuel (ECRA/CSI, 2009). Therefore, biomass with low heating values would have to be blended with other fuels if used in the kiln. The lower process temperature in the pre-calciner allows the use of fuels with low heating values. Also, biomass bulk densities are about one fifth that of coal. Consequently, heating values of biomass fuels are only one tenth that of coal on a volume basis (VDZ and PENTA, 2008). The use of biomass fuels at higher substitution rates may limit or reduce kiln capacity. The high moisture content and low heating values of biomass may lead to an increase in specific energy consumption and reduced energy efficiency.

Wear and/or build up on refractory brick linings can occur with some biomass fuels. Highly abrasive wastes such as dried sludge and unusual particle shapes and sizes can produce operational problems. The trial of grape marc as an alternative fuel at a cement plant was noted to contribute to kiln ring build-up, which reduced the efficiency of kiln operations (Warnken and Giurco, 2003). Further, biomass is difficult to grind or pulverise into small particles. Biomass produces a non-friable, fibrous material during pulverising, which makes it unfeasible to reduce to a size comparable to that of pulverised coal. Consequently, the practice is to reduce biomass to pass a 6.5 mm (¼ inch) mesh. The shape of the product has aspect ratios ranging from three to seven (VDZ and PENTA, 2008).

Another potential challenge to using biomass is that biomass fuel may contain sulphur, chlorine and trace elements such as heavy metals, which could result in other air emission issues or produce compounds in the combustion process that may be detrimental to equipment or clinker quality. In cases when a high volume of chlorine is input, a chlorine bypass system may be necessary in order to avoid operational problems in the cement kiln such as corrosion and blockage, leading to a reduction in efficiencies of kiln operation. When sewage sludge and/or wood waste are used as kiln fuel, mercury input has to be monitored in order to maintain clinker quality and to meet mercury emissions standards (EIPPCB, 2010).

6.2.2 Financial barriers

Re-equipping a plant to handle biomass may require financial investment. This includes the capital cost for new processing and handling equipment (both on and off site) as well as managing the transport and logistics arising from the dispersed nature of the sources of the biomass fuel. For example, in order to be able to process dried sewage sludge in its kiln, ENCI Maastricht invested in two BioMills for grinding sewage sludge. The capital cost can vary significantly depending on the chemical composition and moisture content of the secondary fuels. A Finish cement company Finnsementti Oy has in recent years invested about €2 million in new fuel receiving equipment to enable the use of biomass fuels at its two cement factories. This includes an SNCR system for NOx emissions reduction, a flue gas analysis system and receiving and handling equipment for recycled fuel and biomass (VTT, 2009). Warnken and Giurco (2003) estimated the capital costs for biomass fuel delivery systems to be in the range of A$1 to 3 million. Another cost item associated with the use of biomass fuel is the cost of trials and extra emission monitoring equipment which may not be required if conventional fossil fuels continue to be used. The cost of the trials necessary to obtain a permit to burn those fuels is estimated to be US$0.5 to 1 million (Clark, 2010).

Another potential barrier to increased use of biomass is the cost of biomass fuels. The price of biomass fuels can vary considerably. If surplus supplies are available at nearby sources or municipal solid waste handling facilities, the cost can be very low or the cement plants may even get paid to take the waste fuel. Where there are shortages in biomass supplies and/or competition for the available biomass fuels from other industrial sectors such as power generation, the cost of biomass fuels can be very high. It is expected that the price for biomass will increase significantly in the future (ECRA/CSI, 2009). It may then become increasingly difficult for the cement industry to source significant quantities of biomass at acceptable prices. Adding to this is the transport cost which differs

widely depending on the distances that the biomass fuel travels to the cement plant. The lower density of certain biomass fuels can significantly increase the costs of transport and storage. As mentioned earlier Finnsementti Oy recently invested in new fuel receiving equipment at its cement plants for using biomass fuels. Different biomass feedstocks were tested and the results were promising. Technically, Finnsementti could increase the share of renewable fuels but found the price of the available wood based biomass had been too high (VTT, 2009).

Even if the biomass fuel is free at the point of its generation, transport, preparation and on-site handling can increase the cost per unit energy such that it equals or sometimes exceeds the cost of coal at the burner tip. Operating costs of biomass cofiring are typically higher than dedicated coal systems. A recent study by Hollingshead and Venta (2009) revealed that 10% of the conventional fuel could be substituted by biomass in a cement kiln with fairly simple firing system conversions. This would involve an investment cost of 1.60 \$/t with an increase in operating costs of 0.10 \$/t clinker.

6.2.3 Availability

Necessary investments to start the use of biomass fuels are generally fairly high and the payback period may be long, therefore it is essential for cement manufacturers that a long-term biomass supply, with reasonable costs, is secured. The availability and cost of biomass vary considerably between countries and within countries. In many parts of the world, biomass is more readily available in forested areas whilst in some other areas there are no sufficient biomass resources available. In areas where a large biomass supply is available, there may be high demand for biomass fuels from other industrial sectors such as power generation, metal production and food processing. Competition for available biomass resources is greater close to cities where the energy production may already absorb most of the available biomass fuels (Vesterinen and others, 2010). A recent study on resources, use and markets for biomass fuels found that the availability was the barrier most frequently mentioned (and probably also the most important one) to the increased use of biomass fuels by users and traders (Junginger and others, 2010).

Due to the scale and the energy intensity of cement production, the amount of biomass fuels required can be considerable even at a relatively low substitution rate, and it would be difficult to supply such a high amount of biomass. On the other hand, the cement industry can easily use, in certain proportions, wet and low-calorific value fuels such as sewage sludge, animal meal, and paper sludge. Networks for waste collection, treatment/processing and supply of the biomass derived fuels must be established to allow the utilisation of biomass from these sources. However, in many countries, especially in developing countries, such networks are not adequate or not available at all. Also, in areas with sustainable farming for food, the agricultural waste can be collected, dried and burned in cement kilns.

Overall, the potential to use biomass fuels in the cement industry varies significantly in different regions of the world. Nevertheless, with a large developing international market for biomass, regions with limited biomass resources can reduce their CO_2 intensity through import of bulk biomass at a reasonable cost. Other factors influencing the use of biomass fuels in the cement industry are the local policies and financial measures that support the use of biomass.

6.3   Waste derived fuels (WDF)

Wastes occur in different qualities and forms such as solid, liquid or slurry. Selected waste streams with recoverable energy value can be used as fuels in a cement kiln, replacing conventional fuels. Similarly, selected waste streams containing useful minerals such as calcium, silica, alumina, and iron can be used as raw materials in the kiln, replacing raw materials such as clay, shale and limestone. Fossil fuels and raw materials have been successfully substituted by different types of wastes in cement kilns in Europe, Japan, USA, Canada and Australia for over 30 years. The use of waste

derived fuels can decrease the environmental impacts of wastes, safely dispose of hazardous wastes, decrease greenhouse gas emissions, decrease waste handling costs and save money in the cement industry.

6.3.1 Benefits of using WDF

The use of wastes as alternative fuel in cement kilns has a number of potential benefits such as the recovery of the energy content of waste, conservation of non-renewable fossil fuels, reduction of overall CO_2 emissions, lowering cement production cost and the use of existing technology to safely treat hazardous wastes, eliminating disposal of such wastes through incineration or landfill.

Most alternative fuels used are derived from industrial and domestic waste that is not intended to be used as fuel. The most common industrial wastes that are used as fuel are discarded tyres, waste oils and solvents. Other abundant industrial wastes that often have high calorific values include textiles and paper residue, chemical wastes, plastic, coal slurries and distilled residues, and packaging waste. Domestic waste is available in the form of refuse. Globally, the quantity of waste is high and it is increasing, especially in fast developing countries. Where waste avoidance is not possible, reuse, recycling and recovery become, in most cases, a preferable alternative to final disposal. As such, the utilisation of waste as alternative fuel benefits the community.

Waste materials can be categorised as hazardous and non-hazardous waste. Hazardous waste pollutes both land and groundwater, and may pose risks to human health. Some industrial wastes are heavy polluters and their elimination is problematic and expensive. Modern incineration plants and secure landfills are common options for waste disposal in developed countries. However, they have high investment and operating costs and need qualified personnel. The high temperatures found in a cement kiln are sufficient to dissociate most of the stable toxic molecules, and the residence time in the kiln is comparable to that in typical incinerators (WWF, 2008). In addition, cement kilns operate in an oxidising and alkaline environment and under good mixing conditions an efficient cement kiln can provide an environmentally sound, and cost-effective treatment/recovery option for a number of wastes including hazardous wastes. Virtually any organic compound found in hazardous waste can be completely destroyed at the elevated temperatures in a properly operating cement kiln. Several studies have concluded that co-processing hazardous waste does not affect emissions, and most cement kilns that co-process a wide range of hazardous waste materials can meet emission standards (Vijgen and McDowall, 2008).

Co-processing of waste in cement kilns offers advantages for the cement industry as well as for the authorities responsible for waste management. Cement producers can save on fossil fuel and raw material consumption, contributing to a more eco-efficient production. One of the advantages for authorities and communities is that this waste recovery method uses an existing facility, eliminating the need to invest in a new, purpose-built incinerator or secure landfill site. Also, unlike dedicated waste incinerators, when waste materials are co-processed in cement kilns, ash residues are incorporated into the clinker, so there are no end products that require further waste management. Furthermore, using waste as fuel reduces the environmental impacts of mining, producing, transporting and burning fossil fuels.

The CO_2 emissions reduction potential of substitution of conventional fuels with alternative fuels depends on the CO_2 emission factors related to the energy content of the alternative fuels compared with that of conventional fuels (s*ee* Figure 10, page 38), and the substitution ratio. However, the CO_2 savings from substitution of conventional fossil fuel with WDF go beyond the pure lower emission factors. Figure 11 (*see* page 40) shows the impact of the alternative fuel use on overall CO_2 emissions. While in some cases, the substitution may increase the on-site CO_2 emissions by several per cent due to the higher emission factor of the WDF, the overall emissions are reduced by the use of WDF. As discussed above, if the wastes burned in cement kilns were otherwise incinerated elsewhere, the same

amount of CO_2 would be emitted, or even more if additional fuel is needed in the incineration process. The use of these wastes as cement kiln fuel eliminates the need for the cement kilns to consume non-renewable fossil fuels. Furthermore, the cement kiln recovers energy from the waste more efficiently compared to the thermal efficiency in the incinerator (for example, for electricity generation). The net effect is a reduction of the total CO_2 released to the atmosphere even though emissions at the cement plant itself may not decrease.

6.3.2 Technical challenges

Wastes occur in various forms and qualities. Not every combustible waste is suitable as alternative fuel. Transforming waste to fuel requires certain standards. Before considering the use of waste materials, some basic principles such as appropriate selection of waste materials, a systematic analysis and test, and preparation/pre-treatment of wastes, should be applied. Waste materials used as fuel and/or raw material in cement kilns have to reach different quality standards. Because wastes are highly heterogeneous materials, a WDF quality control system is important. In addition, the use of WDF requires additional storage, handling and dossing equipment.

The strict quality controls for cement products and the nature of the production process mean that only carefully selected waste is suitable for use as alternative kiln fuel. When deciding on the suitability of a waste stream the following should be taken into consideration:
● the origin of the waste and its physical and chemical characteristics;
● health and safety data and hazard classification of the waste;
● intermediate disposal, storage, or treatment of the waste;
● the cost of the waste;
● the existing stock volumes and expected delivery rates;
● the transport conditions such as waste codes, transport mode, legal requirements, etc.

Full-scale testing of a representative waste sample should be carried out to determine all chemical and physical characteristics listed in the operational permit and compare the results against the plant specifications. As a basic rule, waste accepted as an alternative fuel and/or raw material should give an added value for the cement kiln in terms of the heating value of the organic part and/or the material value of the mineral part. In general, wastes with a low heating values and very high heavy metal contents are not suitable for co-processing in a cement kiln. The use of cement kilns as a disposal operation not leading to resource recovery, should only be considered as a means to solve a local waste management problem if there are no other adequate treatment facilities in the area and if such undertaking does not have a negative impact on the environment, public health, or product quality (Holcim/GTZ, 2006; Holcim, 2009).

Some types of waste cannot be used directly as fuel, but must undergo a preparation/pre-treatment process. The resultant waste product should meet both the technical specifications of cement production and the environmental standards. Wastes used in cement kilns should be homogenous with a pre-specified size distribution, and have a stable chemical composition and heat content. The use of hazardous wastes should not detract from smooth and continuous kiln operation, product quality, or the site's normal environmental performance. For optimum operation, kilns require uniform waste material flows in terms of quality and quantity. For certain types of waste this can only be achieved by pre-treatment.

Pre-treatment of solid waste can include drying, shredding, grinding or pelletising depending on the type of waste, and is usually done in a purpose-built facility that may be located either outside or inside the cement plant. The extent of waste processing depends on the specific application. Due to the heterogeneous nature of waste, blending and mixing of different waste streams may be required to guarantee a homogeneous feedstock that meets specifications for use in a cement kiln. However, blending of hazardous wastes should not be conducted with the aim to lower the concentration of

hazardous constituents in order to circumvent regulatory requirements. As a general principle, the mixing of wastes must be prevented from leading to the application of an unsuitable non-environmentally sound disposal operation (Holcim, 2009).

Liquid waste fuels are normally prepared by blending different wastes with suitable heating values and chemistry (like spent solvents or used oil). Normally, only simple pre-treatment such as removal of bottoms, sediments and water is necessary. In some cases, for example when machining oil/emulsions are used as fuel, chemical processes are necessary to remove metallic pollutants and additives.

For optimal operation in cement kilns, that is co-processing with little or no additional emissions, alternative fuels need to be fed to the kiln via appropriate feed points and in adequate proportions, with proper waste quality and emission control systems implemented. For hazardous wastes, the feed point selected must ensure a complete and irreversible destruction of toxic compounds. Adequate feed points should be selected according to the physical, chemical, and if relevant, toxicological characteristics of the waste material used. Hazardous wastes should be introduced in the high-temperature combustion zone of the kiln system such as the main burner, the pre-calciner burner, with sufficient residence time.

More useful information on co-processing waste and hazardous waste materials in cement kilns can be found elsewhere (Holcim/GTZ, 2006; Holcim, 2009; EIPPCB, 2010).

6.3.3 Barriers

Cement kilns are well suited to co-processing a wide range of waste materials. No major technical changes are needed when replacing conventional fossil fuel with WDF. Technically, in cement kilns the fossil fuels can be substituted by WDF by up to 100%. The technology does not pose any real barriers to the utilisation of WDF. The limiting factors are non-technical and lie in areas such as WDF supply, permitting procedure, economics of using WDF, and social acceptance.

Depending on local environmental legislation and regulation, cement producers will need to apply for all the necessary national and/or local permits for co-processing wastes in cement kilns. In some cases, the limited knowledge of the regulators/authorities of the concept of waste hierarchy, the potential of co-processing and its impacts on environment and on health and safety means that it can be difficult for the cement producer to acquire such permits.

The source of waste as an alternative fuel varies widely across regions and countries, and is largely influenced by the types of local industry, the level of establishment of waste legislation and enforcement, waste collection infrastructure and local environmental awareness. Waste management legislation has significant impacts on the availability of WDF. Uncontrolled disposal is usually the cheapest way to get rid of the waste, and the waste generators tend to be unwilling to pay much for adequate disposal. In many developing countries they are often not properly enforced, although laws concerning the controlled handling of waste exist. Not all developing countries have an integrated waste management strategy and only a few can offer an appropriate technical infrastructure that allows controlled collection and pre-treatment of waste materials for alternative fuels. In developed countries where waste management legislation/policies are well established and enforced, landfilling instead of collecting and preparing the waste into alternative fuels may be the preferred option for waste due to its lower costs. In these regions, it is often because there is very limited WDF supply, although there may be sufficient waste materials available as alternative fuel. Even in countries where the land for waste disposal is scarce and/or the waste legislation restricts landfilling and encourages the use of alternative fuel, the availability of WDF can be the key barrier to higher alternative fuel use. For example, the Maastricht cement plant in the Netherlands used 98% alternative fuel to fire its cement kiln in 2008 but dropped to 89% in 2009 due to limited availability (IEA, 2009).
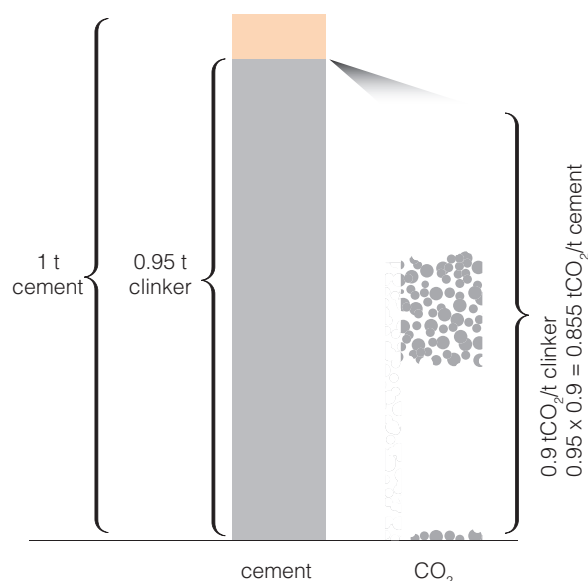
As with the use of biomass fuel, co-processing involvess capital costs for the cement company for the collection, pre-treatment, storage and feeding of WDF to the kiln and of emissions control and reporting, normally in millions of US dollars. The full-scale tests necessary to obtain a permit to burn WDF may cost the cement producer an additional $0.5 to 1 million (Clark, 2010). There are also increased operating costs of co-processing WDF in the cement kiln. Hollingshead and Venta (2009) estimated that the replacement of 15% of fossil fuel in a cement kiln with used tyres would lead to an increase in power consumption of 1.5 kWh/t and in operating costs of 0.10 $/t clinker. The investment cost would be 3.40 $/t clinker.

The cost of the waste material (positive or negative) fluctuates and depends on the price for fossil fuel and primary raw materials, market competition and the costs of alternative treatments. Today in Europe, many alternative fuels have lower or even negative prices compared to conventional fuels. The price of alternative fuel has been projected to increase in future and may rise to around 30% of conventional fuel costs by 2030 and to 70% by 2050 (IEA, 2009). Many waste streams need rather expensive processing before they can be used as kiln fuels and when the overall costs of WDF are higher than the energy and material savings, it will become unviable economically for the cement industry to use alternative fuels. However, this development will be significantly influenced by CO_2 prices.

The level of social acceptance of co-processing waste fuels can strongly affect local uptake. Co-processing waste fuels in cement kilns can be met with strong opposition from the public and non-governmental organisations (NGOs) due to their concern about the impacts of emissions from co-processing over the environment and health, even though emission levels from well-managed cement plants are the same with or without alternative fuel use. The main reasons are the lack of understanding or limited knowledge of the potential of alternative fuel use and of legislative and institutional requirements related to co-processing. Social acceptance can be improved by better information, better public communications and stakeholder engagement.

7   Clinker substitution

Clinker is the main component in most types of cement. For example, the most commonly used type of cement, Ordinary Portland Cement (OPC) is made by grinding a mixture of 95% clinker and 5% gypsum. As discussed in Chapter 3 clinker production is the most energy intensive step in cement manufacturing. CO_2 is emitted during clinker production both from fuel combustion and calcination of limestone. Almost all direct CO_2 emissions from the cement industry come from the clinker making process. Figure 12 shows schematically the amount of direct CO_2 released per tonne of cement produced in relation to the clinker content in the finished cement. It is obvious that reducing the percentage of clinker in the finished cement is the most effective way of reducing CO_2 emissions from cement manufacturing.

Clinker has hydraulic properties, in that it reacts with water and hardens. Other materials containing mineral components also have hydraulic properties when ground and mixed with clinker and gypsum, and therefore can be used as supplementary cementitious material (SCM) in cement. Replacing a portion of the clinker in the cement with other cementitious materials is already practised in many parts of the world. The SCMs that can be used as clinker substitutes include ground granulated blast furnace slag (GGBFS) from the steel industry, ashes from coal combustion and natural pozzolans. Many types of blended cement can be produced depending on the SCM used and the clinker to cement ratio (referred to as clinker ratio). In many concrete applications, the overall performance of a blended cement is better than OPC.
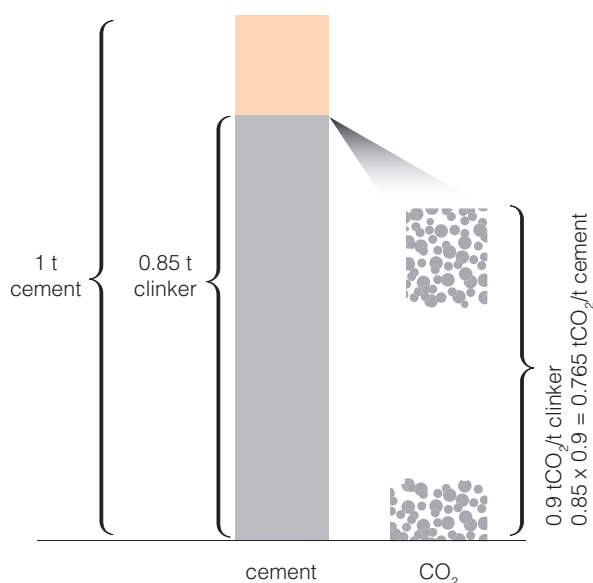
7.1   SCMs

Blended cements contain SCMs that replace a portion of the clinker used. The materials that can be used to make blended cement are broadly divided into cementitious materials and pozzolanic materials. Cementitious materials exhibit characteristics of cement whereas a pozzolan is a material that, when combined with calcium hydroxide ($Ca(OH)_2$), exhibits cementitious properties. Table 12 shows the typical composition of different types of blended cement.

Pozzolanic materials include natural pozzolans and artificial pozzolans. Examples of natural pozzolans include volcanic ash and sedimentary rocks. Artificial pozzolans include

Figure 12   Typical composition of different types of blended cement (IEA, 2007)

Table 12	Typical composition of different types of blended cement (IEA, 2007)			
	OPC, %	Portland fly ash cement, %	Blast furnace slag cement, %	Pozzolanic cement mixes, %
Clinker	95–100	65–94	5–64	45–89
Fly ash		6–35		
Blast furnace slag			36–95	
Pozzolana				11–55
Gypsum	0–5	0–5	0–5	0–5

fly ash from coal-fired power plants, rice husk ash and palm oil fuel ashes. GGBFS exhibits cementitious properties whilst fly ash is a pozzolanic material. Both GGBFS and fly ash are most widely used for blended cements. In addition, limestone is used in some cases as a minor constituent to reduce the clinker ratio. Some other natural pozzolans such as clay and shales need to be activated by thermal treatment and the calcined clay or shale (referred to as manufactured pozzolans) can be used for blended cements.

7.1.1 GGBFS

GGBFS is a by-product from steel making and consists primarily of silicates, alumina-silicates, and calcium-alumina-silicates. The production of blended cement containing GGBFS is very common in Europe and in China. Production of slag cements involves intergrinding of clinker with GGBFS. Extra electricity is needed for blending and grinding and additional fuel may be required for drying. However, the use of GGBFS does not lead to a significant change in overall energy consumption per unit cement produced since the additional power utilisation is largely offset by the power savings from the reduced clinker ratio.

Concrete made with slag cement sets more slowly and has lower early strength development compared to concrete made with OPC, depending on the amount of slag in the cementitious material. However, it continues to gain strength over a longer period in production conditions. This results in lower heat of hydration and lower temperature rises, and makes avoiding cold joints easier, but may also affect construction schedules where quick setting is required. In other words, slag cements have increased ultimate strength and durability and tend to have much better resistance to acids and sulphates and to alkali-aggregate reactions (VDZ/PENTA, 2008). The difficulty of achieving higher strengths at an early stage is the motivation for alkali activation of blended cements. Addition of NaOH to slag cements significantly increases their early reactivity, but there are clear safety implications. This is the reason why high alkali content in clinker is beneficial when producing blended cements. It is also the reason why sodium sulphate (Na_2SO_4) has been added to blended cements by some cement companies (Clark, 2010).

The technical performance and the application of blended cements with very high contents of clinker substitutes are being investigated. In practice, the amount of GGBFS in technically used cements usually ranges from 30% to 70% by weight. The GGBFS normally has a moisture content of 8% to 12% and usually it needs to be dried before grinding. It can be seen from Figure 12 for each tonne of clinker being replaced by GGBFS, approximately 0.9 tCO_2 emissions is avoided (assuming that GGBFS is accounted CO_2-free for cement production). For a cement with 30% to 70% slag, it is estimated that the reduction in thermal energy consumption ranges from 420 to 1880 MJ/t cement. As a result, the emissions of 100 to 430 $kgCO_2$/t cement are avoided (ECRA/CSI, 2009).

7.1.2 Fly ash

Fly ash is obtained from power plants that burn pulverised coal. Fly ash may be siliceous or

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calcareous in nature. The former is a fine powder of mostly spherical particles having pozzolanic properties, whereas the latter may also have hydraulic properties. Like slag cement, fly ash reacts with any free lime left after the hydration to form calcium silicate hydrate (C-S-H), which is similar to the C-S-H formed by the hydration of tricalcium and dicalcium silicates (C_3/S and C_2/S) in the OPC. This process increases the long-term strength and durability, improves sulphate resistance, decreases permeability to water, reduces the water demand, and improves the workability of the concrete. Furthermore, fly ash cements offer a lower alkali-silica reactivity and this allows a reduction in energy consumption needed to remove high alkali containing kiln dusts from the kiln bypass system.

The European standard EN 197-1 allows the production of various types of blended cement with fly ash content from 6% to 55% by weight. In practice, the proportion of fly ash in technically used cements is usually limited to a value of around 25% to 35% by weight (ECRA/CSI, 2009). For some special applications such as roads in China, this ratio has even been increased to 35% to 40% on some pilot sites (WWF, 2008). However, the use of fly ash may be limited by its quality and consistency. Fly ash with excessive unburnt-carbon content (5% or more) will result in a cement with reduced strength, which is a major problem for quality. Fly ash containing ammonia due to the NOx emissions control systems installed on power plants also affects its suitability for use in blended cement. A US company has developed a technology to separate the carbon from the fly ash. This reduces the carbon content in fly ash from 18% to 2.5% and allows the treated fly ash to be used as a clinker substitute. This technology is currently applied in the UK and Israel (IEA, 2007).

The thermal energy consumption of per tonne of cement produced decreases almost linearly with the increased ratio of fly ash in the blended cement. In most cases grinding of fly ash is not necessary, resulting in a reduction in electricity use. For a cement containing 25% to 35% fly ash (by weight), the reduction in thermal energy consumption is estimated to be 220 to 600 MJ/t cement, and power savings of 15 to 27 kWh/t cement are expected. This can be translated into a reduction in direct CO_2 emissions of 50 to 140 kg/t cement and 8 to 19 kg/t cement in indirect CO_2 emissions (ECRA/CSI, 2009).

7.1.3 Silica fume

Silica fume is a by-product of the silicon and ferrosilicon smelting industries. Silica fume is an extremely fine powder with particles about 1/100 of the diameter of an average cement grain. Because of its extreme fineness and high silica content, silica fume is a highly reactive pozzolanic material and is generally used at 5% to 12% by weight in cement for concrete structures that need high strength or significantly reduced permeability to water (NRMCA, 2000). However, the supply of silica fume is limited and the estimated worldwide availability of silica fume is around 2 Mt/y (VDZ/PENTA, 2008). There is a potential health hazard from the inhalation of micro silica and therefore special procedures are required when handling silica fume.

7.1.4 Natural pozzolans

A pozzolan is a siliceous or aluminosiliceous material, which is highly vitreous. This material by itself has few cementitious properties, but will react with lime in the presence of water and the reaction products are the same as cementitious materials except for the C/S ratio. The extent of strength development depends on the chemical composition of the pozzolan: the greater the composition of alumina and silica along with the vitreous phase in the material, the better the pozzolanic reaction and strength display. In general, the use of a pozzolan as a main constituent of cement is possible if the content of reactive silica dioxide is no less than 25% by weight (ECRA/CSI, 2009).

The natural pozzolans most commonly are of volcanic origin. The first known natural pozzolan was

pozzolana, a volcanic ash. In practice, the proportion of pozzolana in technically used cements is usually in the range of 15% to 35% (ECRA/CSI, 2009). Because of the slow pozzolanic reaction pozzolana cements have lower early compressive strength than OPC. However, they have higher long-term strength and improved chemical resistance.

The use of natural pozzolans as a clinker substitute may require additional drying, crushing and grinding prior to use, and then the intergrinding or mixing of the pozzolana with cement clinker. The power consumption is assumed to be slightly lower due to the better grindability of most pozzolanas compared to the clinker replaced. Depending on the extent of drying necessary, replacing 15–35% clinker in a cement with pozzolana could lead to a reduction in thermal energy consumption by up to 600 MJ/t and in electricity consumption by up to 25 kWh/t cement. This may result in a reduction of 140 kgCO_2/t (direct) and 18 kgCO_2/t (indirect) of finished cement (ECRA/CSI, 2009).

7.1.5   Other materials

Manufactured pozzolans

Some naturally-occurring material can be processed to possess pozzolanic properties. Metakaolin and calcined shale or clay are examples of manufactured pozzolans. These materials are manufactured by controlled calcination of naturally occurring materials. Metakaolin is a dehyroxylated form of kaolinite or kaolin. When kaolin is heated to 500ºC to 800ºC, it loses water by dehydroxilisation and becomes metakaolin. Metakaolin is an amorphous, highly pozzolanic material used at 5% to 20% by weight in blended cements. Calcined shale or clay is used at higher percentages (VDZ/PENTA, 2008; NRMCA, 2000). Highly reactive pozzolans, such as silica fume and high reactivity metakaolin can produce high early strength concrete by increasing the rate at which concrete gains strength. Due to the much lower temperature required in the calcination process, the specific fuel consumption used to process these clays into a pozzolanic material is substantially less than the fuel consumption required to produce cement clinker leading to a reduction in CO_2 emissions per tonne of cement produced.

Limestone

Although not classified as a cementitious material or a pozzolan, limestone is also being added to cement in different countries. The use of limestone as a component of cement is now common practice in Canada and Europe. A review of the research conducted in the USA, Canada and Europe over the past 20 years concluded that the use of up to 5% limestone, in general, does not affect the performance of Portland cement (Hawkins and others, 2003). Limestone cements can lead to better workability of the concrete and a lower alkali-silica reactivity. However, for limestone-containing cements to have the same strength as OPC they have to be ground more finely.

The limestone added can work as a fine filler providing additional surface areas for the nucleation and growth of hydration products, generally enhancing the achieved hydration. However, the monocarboaluminate formed by reaction of the limestone with the calcium alumina during cement hydration does not contribute to strength formation. The resistence to acids and sulphates and the freeze-thaw-resistence of limestone-containing cement may be impaired (Bentz, 2006; ECRA/CSI, 2009). A study examining the performance of Portland limestone cement with various limestone contents found that when the limestone content was higher than 15% there were adverse effects on many of the properties of the resultant concrete (Dhir and others, 2007). The US standard ASTM C150 now permits type-I Portland cement to contain up to 5% of ground limestone whilst the European standard EN 197-1 allows the production of various types of limestone cement with limestone contents up to 35% by weight. In practice, the proportion of limestone in cements has been limited to around 25–35% (Bentz, 2006; Hooton and Thomas, 2002). A review by Hooton and Thomas (2002) on the use of limestone as a clinker substitute provides more detail on the influence of limestone on the performance of Portland cement.

A very simple way of replacing a portion of clinker with limestone is to intergrind limestone as a minor or main constituent of cement. Limestone is easy to grind and usually readily available. In general, the production of limestone cement containing 25% to 35% limestone by weight can result in a reduction in thermal energy consumption by 220 to 600 MJ/t cement and a decrease in power demand by 12 to 23 kWh/t. This may lead to a decrease in emissions of direct CO_2 by 50 to 140 kg/t and indirect CO_2 by 6 to 16 kg/t cement (ECRA/CSI, 2009).

7.2   Applications, potentials and limitations

7.2.1   Applications

Replacing a portion of the clinker in cement with SCMs is the most effective way of reducing CO_2 emissions from cement manufacturing and this has been practised in most parts of the world for many years. In some cases, several SCMs are combined. Lower clinker ratio means higher percentage of SCMs are used. The Lafarge Cement WAPCO Plc's CDM Project at Sagamu Cement and Ewekoro Cement Plants in Nigeria aim to reduce the emissions of CO_2 from cement production by switching from OPC to blended cement production. Sagamu Cement and Ewekoro Cement Plant have installed cement production capacity of 1.32 Mt/y and 1 Mt/y, respectively. The blended cement project will gradually reduce the clinker content of WAPCO's Sagamu cement production from about 86.6% in 2005 to 75% in 2017 and that at the Ewekoro Cement Works from 84.7% in 2005 to about 75% over the same time period. The combined total CO_2 emission reduction at the two Cement Works for the 10-year crediting period of 2009 to 2018 is estimated to be about 13.2 MtCO$_2$ (http://cdm.unfccc.int).

Due to different practices, the clinker ratio varies widely from country to country. In general, there has been a gradual decrease in the clinker ratio worldwide since 1990. The decline in the world average clinker ratio (with data available) for 1994 to 2004 was 1.0% per year. The fastest decrease in the clinker ratio of 1.3% per year was observed in China in between 1994 and 2004 (IEA, 2007). Figure 13 shows the regional average clinker ratios for different years between 1990 and 2006.
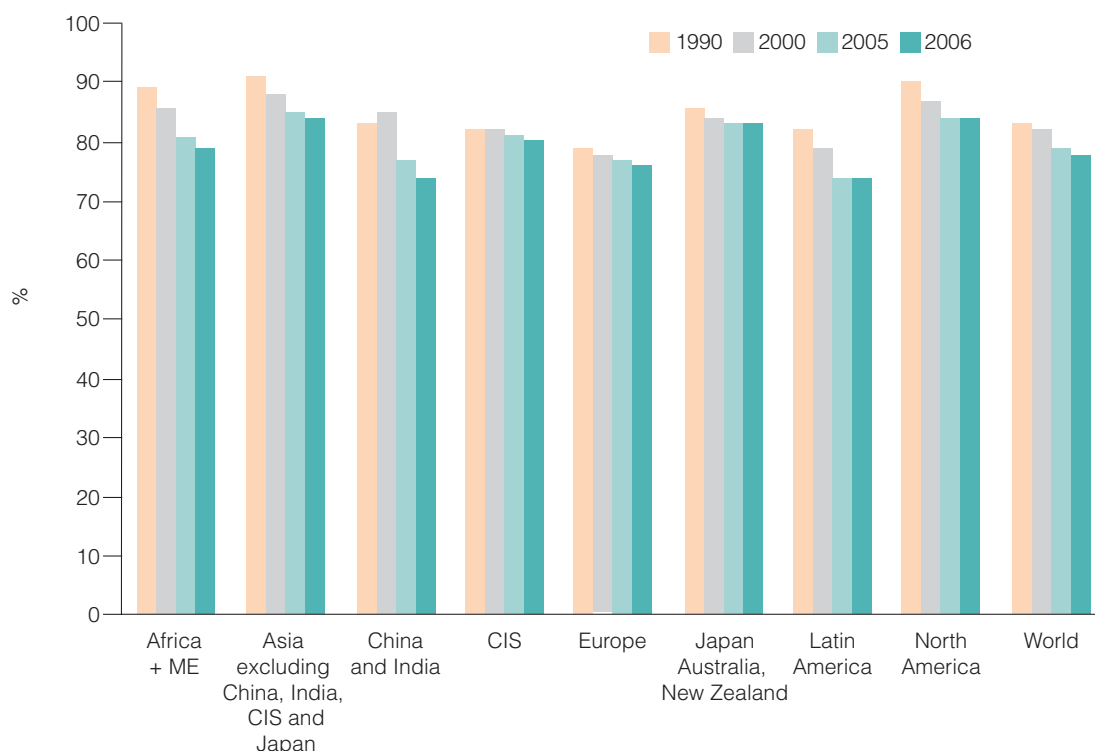

Figure 13 Regional clinker ratios from 1990 to 2006 (WBCSD, 2009)

China is one of the countries that has the lowest clinker ratio in the world due to its extensive use of GGBFS, fly ash, boiler bottom ash and a variety of other substitutes in cement making. In 2005, China produced 330 Mt of fly ash, of which about 63% was used in cement and concrete production (Cui and Wang, 2006). In other words, China alone uses around 210 Mt of fly ash annually for cement and concrete production. In India blended cement accounts for nearly 30% of the cement industry's total output (VDZ/PENTA, 2008).

The European standard EN 197-1 allows wider applications of additives – 25 types of cement using different compositions for different applications are specified in the standard. In Europe, GGBFS and pozzolanic cements account for about 12% of total cement production with Portland composite cement accounting for an additional 44% (VDZ/PENTA, 2008). The average clinker ratio in Europe is lower than the world average figure (*See* Figure 13).

In the USA the consumption and production of blended cement is still limited. The weighted average clinker ratio in this region is higher than the global average figure (*see* Figure 13). However, it should be noted that in the USA and Canada, significant blending of clinker substitutes occurs when the concrete is mixed, rather than at the time of cement production. Obviously, this has important implications for any assessment of the role that clinker substitutes can play in reducing CO_2 emissions from cement production. The clinker ratios presented in Figure 13 have not been adjusted to take into account the use of cement substitutes that are blended directly into the concrete at the time of pouring.

Based on GNR data (WBCSD, 2009), the global weighted average clinker ratio in 2006 was 78%. This was equivalent to more than 500 Mt of clinker-substituting materials being used for the production of 2400 Mt of cement in that year. Of all the companies covered by GNR, the best 10% achieved clinker ratios as low as 68% whilst the best 10% of European manufacturers achieved clinker ratios of 63% in 2006.

7.2.2   Potentials and limitations

Technically, further reduction of clinker ratios to values lower than the current global average are possible but there are issues limiting the implementation of clinker substitution and they are:
- availability of clinker substituting materials;
- prices of the materials;
- properties of the materials and intended application of the cement;
- national standards;
- market acceptance.

The cement plant should be located near the source of the material as the long distance transport of the material would result in significant additional energy use and cost, which is not an attractive option given the low value of the product. Although the clinker substituting materials such as GGBFS, fly ash and limestone are available globally, the regional availability of the materials varies considerably. For example, the use of GGBFS depends on the location and output of blast furnaces for pig iron production. The current availability and use of clinker substituting materials, their advantages and disadvantages as supplementary materials in cement and future availability are compared in Table 13. It is estimated that the annual global production of GGBFS is around 200 Mt (ECRA/CSI, 2009) and much of it has already been used. The supply and the consumption of GGBFS is in balance and therefore the potential for significant increase in its use in clinker substitution is limited (IEA, 2007). The global annual production of fly ash is estimated to be approximately 500 Mt (ECRA/CSI, 2009) and around 50% of it is used (IEA, 2007). Apparently, significant quantities of fly ash are unused. There is considerable opportunity to increase the use of fly ash as clinker substitute. In 2003, the global availability of natural pozzolana was estimated to be 30 Mt but only around 50% of it was used for cement and concrete production (ECRA/CSI, 2009). Opportunity exist to increase in the use of pozzolana in the cement industry. However, deposits of natural pozzolana are located in very few

Table 13 The current availability and use, the advantages and disadvantages and evaluation of their future availability of the main clinker substituting materials (IEA/WBCSD, 2009)

Clinker substitute	Source	Advantages	Disadvantages	Current availability	Future availability
Granulated blast furnace slag	iron or steel production	higher long-term strength and improved chemical resistance	lower early strength and higher electric power demand for grinding	200 Mt (2006)	future iron and steel production volumes are very difficult to predict
Fly ash	coal-fired power plants	lower water demand, improved workability, higher long term strength, better durability (depending on application)	lower early strength, availability may be reduced by change in fuel sources by the power sector	500 Mt (2006)	future number and capacity of coal-fired power plants is very difficult to predict
Pozzolan (volcanic ash, rice husk ash, silica fume)	volcanoes, some sedimentary rocks, other industries	contributes to strength-development, can demonstrate better workability, higher long-term strength and improved chemical resistance	most natural Pozzolanas lead to reduced early strength, cement properties may vary significantly	300 Mt available (2003) but only 50% used	availability depends on local situation – many regions do not provide use of Pozzolana for cement
Manufactured Pozzolan	specific manufacture	similar to natural pozzolans	calcination requires extra thermal energy and so reduces positive CO_2 abatement effect	unknown	very limited availability due to economic constraints
Limestone	quarries	improved workability	maintaining strength may require additional power for grinding clinker	unknown	readily available

areas and its use is limited to cement plants located in close proximity to the source of the pozzolana. Limestone is easily available for most cement plants and its availability will not be limited in foreseeable future.

Evaluating the future available quantity of clinker substitutes worldwide is difficult since it will depend on the growth in other industries like iron making and power generation, and it may be greatly impacted by environmental policy and regulation. For example, with any future decarbonisation of the power sector, the availability of fly ash could be constrained.

An economically viable price is a prerequisite to increase the utilisation of clinker substitution. The price of clinker substitutes varies greatly and depends strongly on transport costs. Current prices are considerably lower than the cost of production of clinker. However, one should bear in mind that in some countries such as China, the USA and some European countries clinker-substituting materials are also used in notable amounts for other purposes than of cement production. An increased demand and/or competition from different applications can result in a rise in prices.

The use of substituting materials depends on their quality and consistency. The properties and elemental constituents of the substituting materials are very important and should be assessed with respect to the intended application of the cement. As discussed above, fly ash with excessive unburnt-carbon content is not suitable for use in blended cement. The homogeneity of GGBFS is an important criterion for its use for slag cement. The properties of blended or composite cement are not exactly the same as those of OPC and therefore it cannot be used in all applications. For example, blended cement with slower reactivity and a longer setting time is a disadvantage in a booming economy where short construction times for buildings are of great importance. In any case, all cement constituents must comply with regulatory requirements and quality standards. In some countries, especially in developing countries, the legal frameworks require composition-based cement standards, which limit the use of clinker substitutes. Switching to performance-based cement categories allows blended or composite cements to develop (WWF, 2008).

Finally, changes in cement product formulations require a significant time before they are incorporated into national standards and accepted in the market. The market acceptance will strongly depend on the performance of the blended or composite cements. It is suggested that the use of blended or composite cements should be promoted to large consumers first, where the number of participants involved is limited and the large quantities facilitate the shift (WWF, 2008).

7.3   Costs

Clinker substitution is the least costly CO_2 reduction method for the cement industry. Even with limited substitution rates, the cost-effectiveness is attractive while the potential CO_2 reduction is significant. Replacing a proportion of clinker with other cementitious materials simply involves intergrinding of clinker with one or more additives and therefore the capital costs are limited to equipment for receiving and storing the substitutes. Retrofitting a facility to allow blending in the finish grinding process may require investment costs ranging from $12 to 18 million (EPA, 2010b). The operational cost savings will depend on the purchase and transport costs of the additives, the increased energy costs for drying when necessary and increased electricity costs for finer grinding, the reduced fuel costs for clinker production and electricity costs for raw material grinding and kiln drive, as well as the reduced handling and mining costs. These costs vary according to location and would

Table 14 Potential reductions in CO_2 emissions using different clinker substitutes and their capital cost effectiveness (Hollingshead and Venta, 2009)				
Clinker substitutes	Ease of implementation	Technology status	Potential CO_2 reduction, kgCO_2/t of cement	CCE, $/t$CO_2$ avoided
Slag	easy	off the shelf	80	12.99
Fly ash	easy	off the shelf	80	12.99
Pozzolan	easy	off the shelf	80	12.99
Manufactured pozzolans	easy	off the shelf	80	12.99
Silica fume	easy	off the shelf	40	19.73

need to be assessed on the basis of individual plant. In general, investment costs for equipment to receive, store and meter the SCMs is estimated at 4.10 $/t clinker. Assuming that cement production is not increased, the reduction in operating cost is a result of producing less clinker and it is proportional to the replacement rate. Proportional power savings will also result from producing less clinker (Hollingshead and Venta, 2009). Table 14 shows the potential CO_2 emissions reductions using different clinker substitutes and their capital cost effectiveness.

In summary, clinker substitution is the most cost-effective way to reduce CO_2 emissions from cement production and it has other environmental benefits. Many clinker substituting materials available for use in blended/composite cements today were previously seen as wastes, often ending up in landfill. Replacing clinker with these substitutes reduces the amount of solid waste and therefore less land is required for landfill. Producing less clinker also means that natural resources such as limestone and fossil fuel are reserved. It is expected that the utilisation of clinker substitution will continue to increase and the world average clinker ratio may be reduced to 70–75% by 2030, and 65–70% by 2050 (ECRA/CSI, 2009).

8　Carbon capture

The cement industry is one of the world's largest industrial sources of CO_2 emissions. As discussed in the previous chapters, the reduction of CO_2 emissions from cement production can be accomplished through different approaches: by improving energy efficiency, by increasing the use of alternative fuels and raw materials, by clinker substitution, as well as by carbon capture and storage (CCS). Up to now, the cement industry has focused on the first three measures and over the last decade or two the cement industry has substantially reduced emissions of CO_2/t cement produced. The scope for further reductions by these means is becoming limited. CCS presents one of the few opportunities to make further major reductions in CO_2 emissions in the cement industry. According to a recent study, CO_2 emissions from cement plants could be reduced by approximately 350 Mt in 2050 if CCS is installed at about 350 modern cement kilns – 10% of all cement kilns worldwide (Taylor and others, 2006).

CCS technology is most frequently discussed in the context of capturing CO_2 from coal-fired power plants. However, CCS is also a key strategy for decarbonising energy intensive industries including cement, oil refineries, iron and steel and chemicals. In cement production almost all of the direct CO_2 emissions come from the clinker burning process and as large CO_2 sources with typically high concentrations of CO_2 in the flue gas (15–30%), cement plants are prime candidates for CCS (Florin and Fennell, 2010). CCS is a set of technologies that captures CO_2 as it is emitted from power plants and other industrial sources, compresses it to a liquid that is then transported in pipelines to be permanently stored deep underground. This report focuses mainly on carbon capture technologies.

8.1　Carbon capture technologies

CO_2 capture technologies can be divided into three main categories: (1) pre-combustion capture;
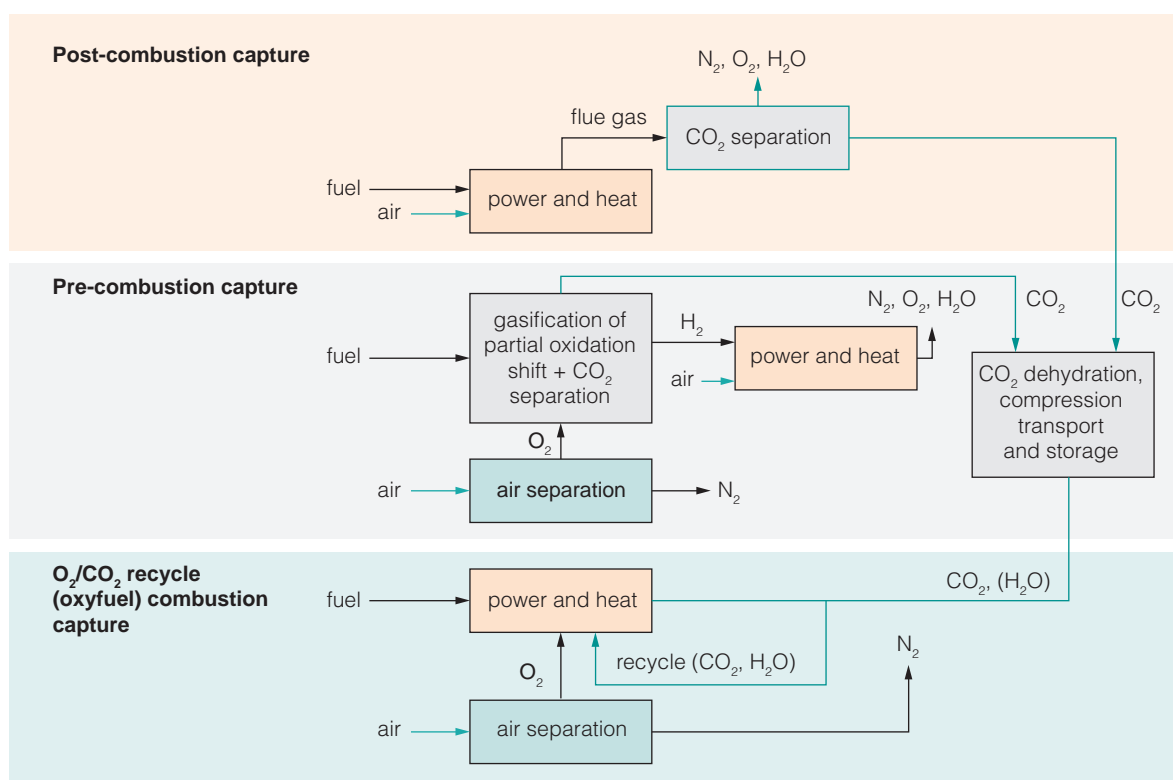

Figure 14　Simplified process schematic of carbon capture technologies (Harland and others, 2010)

(2) post-combustion capture and (3) oxyfuel combustion capture. Pre-combustion capture involves a process called gasification whereby the fuel is reacted with insufficient oxygen (O_2), producing a mixture known as synthetic gas or syngas. Syngas consists of mainly carbon monoxide (CO), methane (CH_4), hydrogen (H_2) and CO_2. Next, a series of reactions converts these gases to a mixture of CO_2 and H_2. After separating from the CO_2, the H_2-rich gaseous fuel can be fired in a range of heaters, boilers, gas turbines or run a fuel cell, while CO_2 is captured and stored. Post-combustion capture is an 'end-of-pipe' technology that separates and captures the CO_2 from exhaust gas using technologies such as absorption/adsorption or membrane processes. In an oxyfuel combustion process, fuel is burned in oxygen instead of air to produce CO_2-rich flue gas. Figure 14 shows the simplified process schematic of these three routes.

The carbon capture technologies potentially applicable for cement manufacture are post-combustion and oxyfuel combustion capture. Pre-combustion capture only addresses the fuel-based CO_2 emissions whilst the major source of the CO_2 emissions from the calcination of limestone in cement production remains unabated. In addition, pure hydrogen has explosive properties and the clinker-burning process would need significant modifications (IEA/WBCSD, 2009). Therefore, pre-combustion capture will not be discussed in this report.

8.1.1 Post-combustion capture

In most cases, CO_2 is captured from a flue gas at low pressure and low CO_2 content and generally, the efficiency of post-combustion capture technologies increases with CO_2 concentration in the off-gas. The clinker burning process produces exhaust gases with relatively high CO_2 concentrations due to the CO_2 from calcination (15% to 30% after preheater compared to 10–15% in coal-fired power plants) and therefore provides more favourable conditions for CO_2 capture than many other industrial processes (IEA GHG, 2008; Hoenig and others, 2007).

Post-combustion capture can be adapted to any combustion or CO_2 producing process. Its main advantage is that it does not require fundamental changes in the clinker making process and hence the process operations would not be drastically affected. As a result, it is suitable for new kilns and in particular for retrofits. It has been estimated that up to 95% of the CO_2 emissions from a cement plant could be avoided if post-combustion capture is implemented (Rootzen and others, 2009). There are several technical approaches to capture CO_2 from flue gas and they are as follows:
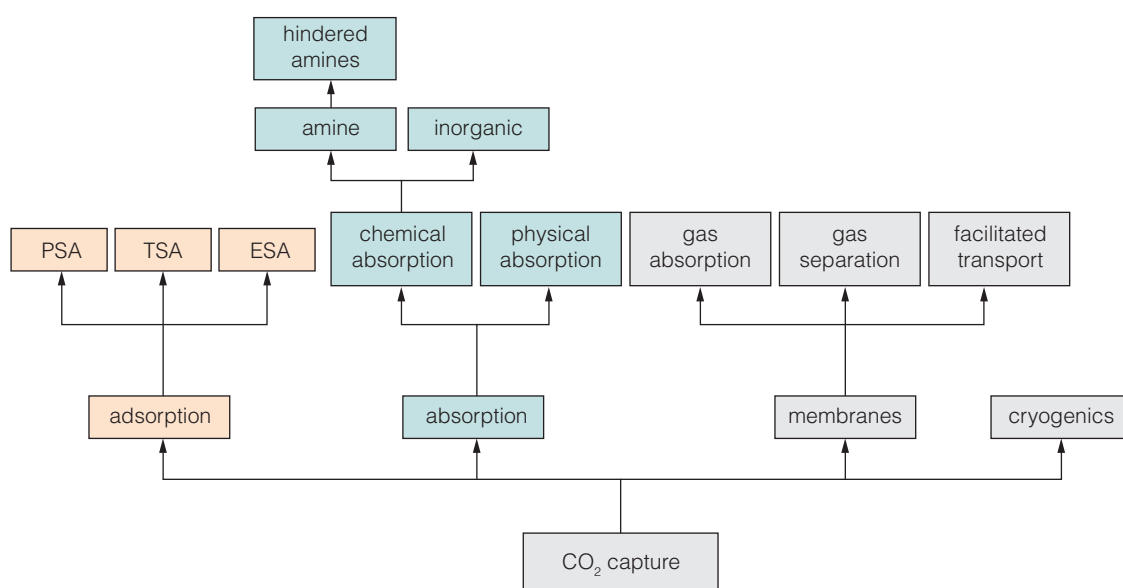

Figure 15 Types of post-combustion CO₂ capture technologies (IEA GHG, 2008)

- separation with chemical/physical solvent (absorption);
- separation with solid adsorbent (adsorption);
- separation with membranes;
- cryogenic separation.

The types of post-combustion CO_2 capture technologies are shown in Figure 15. Some of the chemical and/or physical absorption processes are now commercially available while the adsorption, membranes and cryogenic separation processes, although some have been successfully used in other industrial processes for gas separation, are still under development and are not yet commercially available for CO_2 capture at large-scale power or cement plants.

Absorption processes

Separation of CO_2 from a flue gas can be achieved by physical, chemical absorption or combined chemical and physical absorption (hybrid method), according to the type of bonding between the absorbent and CO_2 formed. In physical absorption, CO_2 is absorbed in a solvent according to Henry's law whilst in chemical absorption, CO_2 reacts with the absorbent, creating chemically bonded compounds. Hybrid systems combine the attributes of physical and chemical absorption. A major difference between chemical and physical absorption is that the solubility of a target gas in physical solvents increases linearly with the target gas partial pressure, while chemical solvents have a high absorption capacity at relatively low partial pressures but reach a plateau at higher partial pressures. Therefore chemical absorption is preferred for the separation of CO_2 at low partial pressures such as in flue gas treatment, while physical absorption is favoured at high partial pressures, for example for syngas treatment.

Chemical absorption processes

A chemical absorption process, also known as chemical solvent scrubbing, is the only commercially-proven technology for capturing CO_2 from low pressure and low concentration flue gases. The majority of chemical solvents currently used are amine based and the most widely used is monoethanolamine (MEA). On contact with an alkaline solvent like MEA, acidic CO_2 reacts forming a dissolved salt and is hence removed from flue gas. The CO_2 is released when applying heat to the absorbent, regenerating the absorbent for reuse in the process. Figure 16 shows a typical solvent scrubbing process for CO_2 capture.
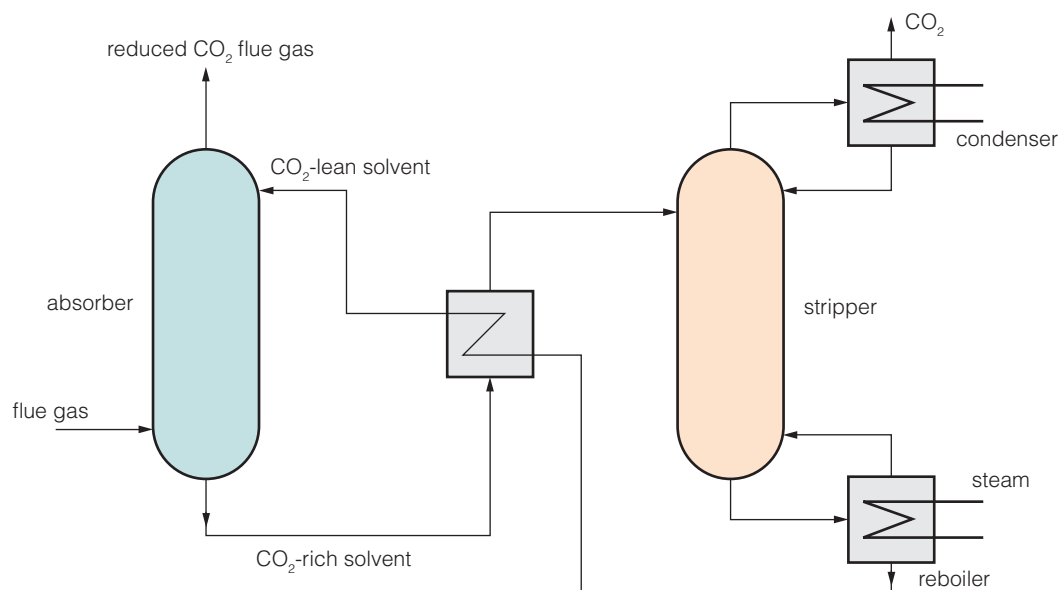

Figure 16 Diagram of a typical solvent scrubbing process for post-combustion CO_2 capture (Hoenig and others, 2007)

Carbon capture

The flue gas is first cleaned of particulates and other impurities such as NOx and SO_2. It then enters the absorption vessel where it is brought into contact with the solvent at temperatures of between 40ºC and 60ºC allowing CO_2 to dissolve into the solvent or chemically react with the absorbent to form a loosely-bound intermediate compound. The flue gas cleaned of CO_2 leaves the absorption vessel and can be discharged into the atmosphere. The CO_2-rich solvent leaving the absorber is fed into the top of a stripper column where the pressure is reduced and/or temperature is increased to between 100ºC and 140ºC in order to release the CO_2 and regenerate the solvent. The lean solvent from the stripper is then cooled and recycled back to the absorber and the process is repeated in a closed loop. The CO_2 stream from the stripper is sent to a compressor ready for storage (Hoenig and others, 2007; IEA GHG, 2008).

The chemical absorption process is the leading technology currently used for post-combustion CO_2 capture. It has been used in chemical, refinery and gas processing industry for decades. Its advantages include high capture efficiency, selectivity, and lower energy use and costs than other capture processes. One of the major disadvantages of amine absorbents is that they are often degraded by oxygen (O_2) and impurities such as SOx and NOx in the flue gas. The presence of oxygen in the flue gas increases the corrosion and solvent degradation in the absorption system. Other disadvantages of amine-based absorbents include low CO_2 loading capacity, high energy consumption during absorbent regeneration, equipment corrosion, large footprint, and removal and disposal of solvent degradation products. More detail can be found in a recent review of solvent scrubbing technologies by Davidson (2007).

Research into chemical scrubbing with amine solvents is focused on the design of new solvent molecules and/or blends of existing solvents, together with the mitigation of problems such as corrosion. The blends of existing solvents exploit the desirable characteristics of different solvents, for example, the high capture rate for primary and secondary solvents with the high ultimate CO_2 uptake for tertiary solvents (Florin and Fennell, 2010). To improve the performance of amine solvents, sterically hindered amines have been developed that require less energy for absorption and regeneration, and have higher CO_2 loading capacity compared with uninhibited alkanolamines such as MEA and diethanolamine (DEA). KS-1 and KS-2 are two such proprietary sterically hindered amines developed by Kansai Electric Power Company (Kepco) and Mitsubishi Heavy Industries (MHI). A KS-1 scrubbing process has been in commercial operation in a fertiliser plant since 1999. These amines have the advantage of a lower circulation rate due to a higher CO_2 loading capacity, a lower regeneration temperature and a lower heat of reaction. They are also non-corrosive to carbon steel at 130ºC in the presence of oxygen (Hoenig and others, 2007; IEA GHG, 2008).

Inorganic alternatives to amine-based scrubbers are also commercially available. Such processes use alkali salts of weak acid as absorbent and the most popular salts used have been sodium carbonate and potassium carbonate. Several inorganic solvent scrubbing processes using potassium carbonate have been developed and information on these systems can be found elsewhere (Hoenig and others, 2007). The main advantages of inorganic solvent scrubbing process are the low cost and minimal degradation of the solvent. However, sodium and potassium carbonate aqueous solutions have a number of problems in practice: low reaction rates with CO_2, higher energy consumption for regeneration compared to the alkanolamine based processes, and a high rate of equipment corrosion. In addition, solution concentrations are limited by the precipitation of bicarbonate salts and solution temperatures are high. Foaming is also reported to be a concern. Some measures may be taken to tackle these problems. For example, potassium carbonate can be used in combination with promoter(s) for CO_2 separation, and various corrosion inhibitors have been employed effectively in some circumstances.

Intensive research is being carried out into the investigation of alternative solvents with the aim of reducing energy consumption for solvent regeneration. Various novel solvents are being tested and one of the most promising is aqueous ammonia. The perceived major advantages that aqueous ammonia has over amine scrubbers (and MEA in particular) include (IEA GHG, 2008):
● higher CO_2 removal efficiency (99% compared to 94% for MEA);

	Solvent name	Solvent type	Process conditions
Physical solvent	Rectisol®	methanol	−10/−70ºC, >2 MPa
	Purisol®	n-2-methyl-2-pyrolidone	−20/+40ºC, >2 MPa
	Selexol™	dimethyl ethers of polyethyleneglycol	−40ºC, 2–3 MPa
	Fluor solvent™	propylene carbonate	below ambient temperatures, 3.1– 6.9 MPa
Chemical solvent	MEA	2,5n monoethanolamine and inhibitors	40ºC, ambient to intermediate pressures
	Amine guard	5n monoethanolamine and inhibitors	40ºC, ambient to intermediate pressures
	Econamine^SM	6n diglycolamine	80–120ºC, 6.3 MPa
	ADIP®	2-4n diisopropanolamine 2n methyldiethanolamine	35–40°C, >0.1 MPa
	MDEA	2n methyldiethanolamine	
	Flexsorb®	hindered amine	
	KS-1, KS-2, KS-3		
	Benfield™ and versions	potassium carbonate and catalysts. Lurgi & Catacarb processes with arsenic trioxide	70–120ºC, 2.2–7 MPa
Physical/chemical solvent	Sulfinol®-D Sulfinol®-M	mixture of DIPA or MDEA, water and tetrahydrothiopene (DIPAM) or diethylamine	>0.5 MPa
	Amisol®	mixture of methanol and MEA, DEA, diisopropylamine (DIPAM) or diethylamine	5/40ºC, >1 MPa

Table 15   Commercial absorption solvents used in industry for CO_2 separation (IEA, 2008)

- high CO_2 loading capacity (1.2 $kgCO_2$/kg NH_3 compared to 0.4 $kgCO_2$/kg MEA);
- NH_3 is much cheaper than MEA;
- less energy is required for regeneration than amine scrubbers;
- aqueous ammonia can remove acid gases like SO_2, NOx and CO_2 simultaneously, which may result in a simple emissions control system and a reduction of total cost.

However, challenges remain to the use of aqueous ammonia solvent. Ammonia has high volatility and tends to vaporise in the absorption tower and escape with the flue gas (ammonia slip). To mitigate this the absorption process must take place at either elevated pressure or very low temperature with additional tail gas control measures. The regeneration process also takes place at an elevated pressure. One such process currently under development is the chilled ammonia process.

The chilled ammonia process (CAP) is being developed by Alstom and 5 MWt pilot-scale tests have been carried out on a coal-fired power plant in the USA and a gas-fired plant in Sweden (Hilton,

2009). The CAP captures CO_2 from flue gas by direct contact with ammonium carbonate solution at temperatures between 0ºC and 10ºC. The process consists of a flue gas cooling system, an absorption and a regeneration system. In the primary absorption reaction, ammonium carbonate reacts with CO_2 to form ammonium bicarbonate, which precipitates as a solid. The CO_2-rich solution is pumped through heat exchangers to heat the solution to temperatures above 80ºC to dissolve the solids prior to injection into the regenerator. In the regenerator the chemical reaction is reversed with the application of heat. CO_2 released by the regeneration reaction pressurises the system.

Cooling the flue gas to 0ºC to 10ºC condenses the moisture (H_2O) in the flue gas and eliminates the residual contaminants such as SO_2, NOx, HCl and condensable particulates. The low temperature also reduces the flue gas volume and increases the flue gas CO_2 concentration leading to a higher capture efficiency with low ammonia slip. The other main features of CAP include the lower energy consumption for regeneration due to the low heat of vaporisation, lower sensible heat loss due to high CO_2 loading, regeneration at >20 bar (2 MPa) and at >120ºC to generate a high pressure CO_2 stream that results in reduced CO_2 compression energy (Kozak and others, 2009; Hilton, 2009; Rhudy and Black. 2007). It was reported that CAP uses only 15% of the amount of steam consumed by MEA for regeneration (Rhudy and Black, 2007). However, electricity is required for refrigeration, and therefore the overall efficiency may represent only a marginal improvement compared to amine scrubbing. The CO_2 capture efficiency of CAP is expected to be 90% and high purity CO_2 steam is produced. A pilot CAP facility was being installed on a 20 MWe slip stream from the FGD outlet of the Mountaineer coal-fired power plant in the USA to further test the technology (Hilton, 2009).

Physical absorption processes

In physical absorption, the solvent can be regenerated by either heating or pressure reduction using less energy than that of chemical absorption. The commercially available CO_2 scrubbing solvents used in industry are shown in Table 15. The CO_2 removal efficiency of the physical solvents is around 90%. The physical absorption process is not considered suitable for carbon capture from a conventional cement plant. Recently, active research has been carried out to investigate ionic liquids (ILs) as an absorbent for post-combustion CO_2 capture. The major advantages of ILs are that they are non-volatile and therefore the risks of contaminating the purified CO_2 stream and solvent losses are minimal, they are non-corrosive, and the physical properties may be tuned to enhance the reaction rate and increase the product selectivity. In addition, ILs can effectively remove SO_2 from the flue gas without degradation of the IL. However, ILs are currently prohibitively expensive, and they have other drawbacks (Florin and Fennell, 2010; Wappel and others, 2009).

Adsorption processes

Adsorption processes remove CO_2 from a gas stream by selectively adsorbing CO_2 molecules onto the surface of a solid adsorbent. Adsorption is not yet considered attractive for large-scale separation of CO_2 from flue gas and it is certainly not a mature technology for potential application at cement kilns because the capacity and CO_2 selectivity of the available adsorbents are low. Many novel sorbents are beng tested and chemisorption with high temperature solid sorbents appears to be a promising technology. The leading candidate is calcium oxide (CaO) derived from limestone. CaO can react with CO_2 to form calcium carbonate ($CaCO_3$) at temperatures around 600ºC (carbonation process). The reaction can be reversed by calcining $CaCO_3$ into CaO and CO_2 at around 1000ºC (calcination process). The carbonation-calcination cycle (also referred to as carbonate looping or Ca-looping) was successfully tested in experimental settings and at a pilot plant (IEA GHG, 2008). One of the main challenges is to reduce the large amounts of sorbents required due to the degradation in adsorption activity over repeated cycles. It also generates a new waste stream. To this aspect, Ca-looping may be more suited to CO_2 capture in a cement plant because the exhausted sorbent can be used as a feedstock for clinker making and therefore, the cost of sorbent is minimal resulting in a significant reduction in the total cost of CCS. Another potential advantage of using Ca-looping for CO_2 capture at a cement plant is its low energy efficiency penalty which is expected to be lower than 6% (Bosoaga and others, 2009). It has been proposed to integrate a cement plant and a power plant using oxyfuel combustion as well as a Ca-looping system for CO_2 capture for both plants. The synergy has several

potential advantages. Firstly, the coal ash from the power plant and the purge stream of CaO from the Ca-looping cycle can partially replace limestone as raw feed to the cement kiln. Since the CaO and coal ash are already decarbonised, the process CO_2 emissions per unit of clinker produced are lower. The fuel consumption for calcination is also reduced. Secondly, the heat generated by the exothermic carbonation reaction in the CO_2 capture vessel and the waste heat from the cement kiln can be used in the power plant to generate electricity. The overall energy efficiency is therefore improved leading to lower fuel-combustion related, direct and indirect CO_2 emissions. The modelling and analysis done by Romeo and others (2011) showed that around 94% of CO_2 emissions can be avoided by integration of a cement plant, a power plant and a Ca-looping system. The CO_2 saving costs of such synergy could be as low as 12.4 €/tCO_2 emissions avoided. The main limitation of the Ca-looping process is that the sorbent reactivity and durability decrease considerably with the number of cycles. The sorbent degradation is exacerbated in the presence of SOx in the flue gas.

The potential synergy between power generation, cement manufacture and CO_2 capture using Ca-looping has been investigated at Imperial College, UK in the past three years (Dean and others, 2011a,b; Blamey and others, 2010). Several other independent projects have been initiated in order to scale-up Ca-looping technology, including pilot plant trials with capacities up to 120 kWt in the USA, Canada and Spain. These projects have demonstrated that 80–90% CO_2 capture efficiencies can be achieved using Ca-looping cycles. Large-scale demonstrations (~2 MWt) are also planned. More information on these projects can be found elsewhere (Dean and others, 2011b).

Other alkali and alkaline earth metal oxides that have similar chemical properties may potentially be used as sorbents in carbonate looping process.

Membrane separation

Membranes are specially manufactured porous materials that allow the selective permeation of different gases through them. Membrane processes can achieve higher than 80% CO_2 separation efficiency. The main advantages of membrane separation processes are that no regeneration energy is required and no waste streams are generated, and the membrane separation units are small in size and simple to operate. In membrane separation processes, the energy is consumed mainly to either pump up the flue gas to a higher pressure to provide a driving force for the separation, or to apply vacuum to the permeate. However, membranes are sensitive to sulphur compounds and other trace elements. Membranes cannot usually achieve a high degree of separation and consequently, multiple stages and/or recycle of one of the streams is necessary leading to increased complexity, energy consumption and costs. Although it seems unlikely at the moment, the technology may play a key role in the future in CO_2 capture in the cement industry (Florin and Fennell, 2010; Hoenig and others, 2007).

Cryogenic separation

Cryogenic separation exploits the different boiling temperatures and partial pressures of the gases in a mixture which can be separated into distinct phases by cooling or compression. Cryogenic separation has the advantage that it produces liquid CO_2 ready for transport to the storage site. Its major disadvantage is the amount of energy required to provide the refrigeration necessary for the process, particularly for dilute gas streams. Another challenge is that some components such as water have to be removed before the flue gas is cooled to avoid ice formation and corrosion (Zanganeh and others, 2009). Cryogenics would normally only be applied to high concentration, high pressure gas streams. The most promising applications of cryogenic separation for carbon capture in the cement industry are predicated on oxyfuel combustion capture in which the flue gas has a high concentration of CO_2.

8.1.2   Oxyfuel combustion

In oxyfuel combustion, fuel is burned in pure O_2 instead of air and this results in a flue gas that is composed mainly of CO_2 (>80%) and water vapour, which is easily separated at low cost by the condensation process. An air separation unit (ASU) will be required to deliver oxygen to the oxyfuel

combustion process. When fuel is burnt in pure oxygen flame, temperatures in excess of 3500ºC can be achieved. High flame temperature could cause refractory damage and increase the formation of NOx. To control this a proportion of the CO_2-rich flue gases is recycled back to the combustion zone, as a diluent, to moderate the temperature.

The high concentration of CO_2 in the flue gas eliminates or reduces the need for costly post-combustion capture systems. However, the major cost and energy penalty of post-combustion processes is traded here for the costly and energy-intensive oxygen production, typically by cryogenic air separation. In addition it is extremely challenging to introduce oxyfuel combustion technology with flue gas recirculation into an existing cement plant. To prevent air in-leak, the complete plant has to be sealed or has to be operated with excess pressure. A new ASU has to be installed on the cement plant premises and the facilities of flue gas recirculation have to be included in the existing plant units. The different flue gas enthalpy and flows require a different clinker cooler efficiency. Consequently all plant units have to be redesigned to the requirements of the new technology. Hence implementation of oxyfuel combustion with flue gas recirculation seems to be predominantly an option for new plants (Hollingshead and Venta, 2009). Also, it is generally understood that at very high temperatures and oxygen concentrations cement kiln wall deterioration will increase. Therefore, there is a balance between achieving the high temperatures for the cement production process and having to replace the kiln wall lining. Changing the atmosphere within the combustion chamber will have a significant effect on the heat transfer characteristics because the radiant heat fluxes and convective heat transfer performance are a function of the gas composition in the combustion chamber (Barker and others, 2009). Furthermore, oxyfuel combustion will have some effect on the calcination process due to the much higher CO_2 concentration in the calciner. Higher temperatures may be required for the calcination as set by the equilibrium partial pressure of CO_2 above CaO.

The production of oxygen is a key step in an oxyfuel combustion system. Oxygen can be produced on the cement plant premises by different methods. When a large quantity of oxygen is required a cryogenic air separation unit, which is well developed and widely used, is the preferred choice. The cost of oxygen production by cryogenic separation amounts to 54 $/t of O_2 produced and the power consumption is in the range of 0.2 to 0.35 MWh/t of O_2 (Hollingshead and Venta, 2009). The following is a brief discussion of some of the processes being explored that could reduce the cost of oxygen production.

Ion transport membranes

In comparison to cryogenic air separation, oxygen production by membranes may provide a cheaper solution, both in terms of capital and operating costs. Ion transport membranes are semi-permeable ceramic mixed metal oxide membranes that can be used to separate oxygen from a stream of heated air. A voltage or pressure differential across the membranes causes oxygen ions from the air flow to migrate through the membrane where, on the other side, they combine to form oxygen gas and electrons. These membranes operate at temperatures similar to those of the tertiary air drawn from the cooler for combustion in the pre-calciner of a modern cement kiln and as such offer potential for integration into the cement making process (IEA GHG, 2008).

Chemical-looping combustion

Chemical-looping combustion is based on the use of metal/metal oxide to provide a reversible chemical reaction for oxygen supply. The developments in this technology are reviewed in detail by Henderson (2010) in a recent IEA Clean Coal Centre report. The technique involves the use of a metal oxide such as the oxides of Ni, Co, Fe, Cu and Mn, as an oxygen carrier that transfers oxygen from combustion air to the fuel, and hence a direct contact between air and fuel is avoided. Fuel combustion is split into separate oxidation and reduction reactions in two inter-connected fluidised bed reactors, an air reactor and a fuel reactor. In the air reactor, a suitable metal reacts with air and is oxidised into a metal oxide. The metal oxide is then circulated to the fuel reactor where it reacts with fuel and is reduced back to metal. The exit gas stream from the fuel reactor contains mainly CO_2 and H_2O, and the metal is recycled back to the air reactor where it is oxidised and the process is repeated. Depending on the metal oxide and fuel used, the metal oxidation reaction is often endothermic, while

the metal reduction reaction is exothermic. The total amount of heat evolved from the reactions is the same as for normal combustion where the oxygen is in direct contact with the fuel. This so called 'flameless combustion' avoids the need for energy intensive air separation to provide pure oxygen. Chemical-looping, as currently embodied, is not suitable for cement manufacture.

8.2   CCS costs and status

In cement production, CO_2 is emitted from two sources: fuel combustion and limestone calcination in the kiln. These two CO_2 sources and the nature of the cement manufacturing process require industry-specific carbon capture techniques that are efficient and low in cost. Some capture technologies that appear to be appropriate for potential applications at cement kilns have been discussed above. These technologies and their main technical challenges are summarised in Table 16.

Table 16 Summary of the main carbon capture technologies and their technical challenges (Florin and Fennell, 2010)		
	Technology	Technical challenge
Post-combustion capture	solvent scrubbing, eg MEA, KS-1, MDEA, chilled ammonia, (TRL* = 6)	high energy requirements, high degradation rates, environmentally hazardous solvent degradation products, potential problems due to equipment corrosion, requires very large equipment
	low-temperature solid sorbents, eg supported amines (TRL = 2–3)	relatively low capture capacity, no experience under realistic conditions
	ionic liquids (TRL = 2–3)	very expensive, complicated manufacturing process
	biological capture using algae ponds or bioreactors (TRL =2)	scale-up challenges due to growth rate of algae populations – may be overcome with genetically engineered species
	high-temperature solid sorbent, eg post-combustion carbonate looping (TRL = 4–5)	drop-off in CO_2 capture capacity of sorbent derived from natural limestone associated with exposure to impurities and physical decay
	membrane separation technology for CO_2 separation from flue gas (ie N_2) (TRL = 2–3)	high cost of materials, life-time and reliability issues with to exposure to impurities, demonstration of large-scale pressure/vacuum equipment, efficient integration with power scheme
Oxy-combustion capture	oxyfuel boiler with O_2 separation from N_2 by cryogenic air separation (TRL = 5)	costly and energy intensive air separation, temperature moderation due to high flame-temperature when fuel is combusted in concentrated O_2
	chemical-looping-combustion using solid metal oxygen carriers (TRL =4)	degradation of oxygen carriers during long-term cycling, most significant when using coal or biomass
	membrane separation for O_2 separation from N_2 with ion-exchange membrane (TRL = 2–3)	high cost of materials, life-time and reliability issues with to exposure to impurities
* Technology readiness levels rank technologies between 1 (basic principles observed and reported), through intermediate levels (technology or part of technology validated in a working environment), to a maximum of 9 (technology deployed.		

Research on carbon capture within the cement sector has started only recently. It is still at an early stage and consequently, the operational experiences with CO_2 capture in the cement industry are very limited. A summary of the key research activities can be found in a recent report by Mott MacDonald (2010). Some technical issues will have to be solved before the CO_2 capture processes can be tested

Table 17 Comparison of the maturity of CO_2 capture technologies and their potential application at cement kilns (Hoenig and others, 2007)

	Post-combustion				Oxyfuel
	Chemical absorption	Physical absorption	Adsorption	Membranes	
Maturity of technology	commercial in selected industrial sectors	commercial in selected industrial sectors	research and pilot-scale level	research level	research and pilot-scale level
Applicability to cement kilns	yes	unlikely	unlikely	yes	yes
CO_2 capture	fuel CO_2 and process CO_2	fuel CO_2 and process CO_2	fuel CO_2 and process CO_2	fuel CO_2 and process CO_2	fuel CO_2 and process CO_2
Retrofit	yes	yes	yes	yes	no
Assessment for R&D	yes	unlikely	unlikely	yes in the long-term	yes

Table 18 Cement plant performance with and without CO_2 capture (Barker and others, 2009)

	Unit	Base case, no capture	Post-combustion capture	Oxy-combustion capture
Fuel and power				
Coal feed	kt/y	63.3	391.6	72.1
Total fuel consumption (LHV basis)	MW	96.8	304.0	97.8
Average power consumption	MW	10.2	42.1	22.7
Average on-site power generation	MW		45.0	0.7
Average net power consumption	MW	10.2	-2.9	22.0
CO_2 emitted and captured				
CO_2 captured	kg/y		1067.7	465.0
CO_2 emitted on-site	kg/y	728.4	188.4	282.9
CO_2 emissions avoided at the cement plant	kg/y		540.0	445.6
	%		74	61
CO_2 associated with power import/export	kg/y	42.0	−11.8	90.8
Overall net CO_2 emissions	kg/y	770.4	176.6	373.7
CO_2 emissions avoided, including power import and export	kg/y		593.8	396.8
	%		77	52

and/or deployed on commercial cement kilns. Table 17 compares the maturity of different CO_2 capture technologies and their potential applications in the cement industry. The performance of a cement plant with and without CO_2 capture is shown in Table 18.

Although not yet proven at the industrial scale in cement production, these technologies are potentially promising. However, from a technical point of view, carbon capture technologies in the cement industry are not likely to be commercially available before 2020. Before then, research and pilot tests are needed to overcome the technical challenges and to gain practical experiences with these new developing technologies. According to the IEA, large-scale demonstration projects (especially on post-combustion technologies) will be initiated between 2015 and 2020. After 2020, CCS could become commercially deployed in the cement industry if the political framework is supportive and social acceptance is achieved (IEA/WBCSD, 2009).

The capital investment for a new CO_2 capture plant and operating costs for separating, compressing, transporting and storing the CO_2 will impose a considerable economic burden on cement manufacturers. The costs of carbon capture will therefore be a decisive factor in its future application in the cement industry. The costs for all the above discussed technologies are high. The current estimated costs for CO_2 capture in a cement plant range from 20 to 50 €/tCO_2 captured (27–67 $/t). The costs based on the avoided CO_2 emissions, which are estimated to be in the range between 24 and 75 €/tCO_2 (32 and 101 $/t$CO_2$), are higher because that the installation of CO_2 capture systems will reduce the overall efficiency of cement production (Hollingshead and Venta, 2009). The current carbon capture processes require large amounts of energy. Installation of such a system in a cement plant may reduce the energy efficiency of the clinker burning process by 30–40%. In general, the CO_2 capture costs are lower for larger kilns than small- or medium-sized kilns. The costs of carbon capture may decrease in the future according to technical and scientific progress and as knowledge is gained from operation of carbon capture systems at power plants.

Implementing CO_2 capture process in cement plants has significant impacts on cement production costs. A recent study analysed the cement production costs with and without CO_2 capture based on a 5-stage preheater and pre-calciner dry process cement plant with a capacity of 1 Mt/y and the results are shown in Table 19. It is clear to see from Table 19 that carbon capture processes require high

Table 19   Cement production costs with and without CO_2 capture (Barker and others, 2009)

	Base case, no capture	Post-combustion capture	Oxy-combustion capture
Capital costs, € million per year	263	558	327
Operating costs, € million per year			
Fuel	6.7	21.5	6.9
Power	4.0	−1.1	8.7
Other variable operating costs	6.1	10.6	6.4
Fixed operating costs	19.1	35.3	22.8
Capital charges	29.7	63.1	36.9
Total costs	**65.6**	**129.4**	**81.6**
CO_2 abatement costs, €/t			
t cement product		63.8	16.0
tCO_2 captured		59.6	34.3
tCO_2 emissions avoided		107.4	40.2

capital investments. The costs of cement production with post-combustion CO_2 capture are almost double the production costs without carbon capture. The costs for oxyfuel combustion are estimated to be 40 €/tCO_2 avoided at a 1 Mt/y European cement plant and 23 €/tCO_2 avoided for a 3 Mt/y plant in Asia. The estimated costs of post-combustion capture are substantially higher at 107 €/tCO_2 for a 1 Mt/y European cement plant and 59 €/tCO_2 for a 3 Mt/y Asian plant (Barker and others, 2009).

It can be seen from Table 18 and Table 19 that post-combustion capture (chemical absorption with amine based solvent) technologies have higher CO_2 capture efficiencies than oxyfuel combustion. However, the capital and operating costs of post-combustion capture are considerably higher compared with oxyfuel combustion. This is because of the need to install FGD and NOx control systems when implementing post-combustion CO_2 capture to a cement kiln, the relatively high costs of providing steam for solvent regeneration from a modest-sized CHP plant, and the lower economies of modest plant size. Use of alternative solvents and integration with an adjacent power plant could more than halve the costs (Barker and others, 2009). Also, as discussed above the costs will be much lower than those quoted in Table 18 and Table 19 if Ca-looping is applied to an integrated cement and a power plant.

In another recent study, Hollingshead and Ventas (2009) compared the costs of carbon capture technologies based on capital cost effectiveness (CCE) and their results are summarised in Table 20. The results from their study showed that the potential CO_2 capture efficiency of oxyfuel combustion was comparable to that of post-combustion capture but the CCE of oxyfuel combustion is significantly lower compared with post-combustion capture technologies.

Results from these studies suggest that the oxyfuel combustion offers a cost-effective solution for CO_2 capture at new-build cement plants. However, more research and development is needed to address a number of technical issues to enable this technique to be deployed.

In summery, scaling up existing CCS processes and integrating them with cement kilns poses technical, economic and regulatory challenges. Detailed studies identifying the barriers to the widespread, cost-effective deployment of CCS have recently been published and plans to overcome these barriers have been proposed (ITF, 2010; IEA, 2008). Currently, the costs of CO_2 capture are very high and the high costs could inhibit widespread commercial deployment of CCS. Investments in CO_2 capture will occur only if the technology is commercially available at economically competitive prices and supportive national policy frameworks are in place.

Table 20 Comparison of carbon capture technologies based on capital cost effectiveness (CCE) (Hollingshead and Venta, 2009)

Technology	Ease of implementation	Stage of technology	Potential CO_2 reduction, kgCO_2/t cement	CCE, $/t$CO_2$ avoided/y
Chemical absorption	Complicated	commercial in selected industrial sectors	622	126
Membranes	complicated (early stage of development)	research and pilot scale level	600–660	unknown
Oxy-combustion	complicated	research and pilot scale level	659	74

9 Low-carbon cements

The cement industry is a major contributor to anthropogenic CO_2 emissions. Every year, billions of tonnes of CO_2 are released into the atmosphere from cement production. Ordinary Portland cement (OPC) is by far the most commonly produced type of cement. The principal raw material needed to produce OPC is limestone. As discussed in Chapter 3, the CO_2 released in cement production can be divided into two categories: fuel combustion related CO_2 and process related CO_2. The kiln feed for clinker contains five major oxides and several trace elements. The five major oxides are SiO_2, Al_2O_3, Fe_2O_3, CaO and MgO. Only SiO_2, Al_2O_3, Fe_2O_3, and CaO take part in the reactions that form the clinker minerals. Although SiO_2, Al_2O_3 and Fe_2O_3 are normally present in raw materials as oxides, CaO and MgO require most of the heat used to produce cement clinker. CaO is formed in the kiln from $CaCO_3$ (limestone) and MgO is formed in the kiln from $CaMg(CO_3)_2$ (dolomite) (Young and Miller, 2004) according to the chemical reactions shown below:

$$CaCO_3 + heat \rightarrow CaO + CO_2$$
$$800 - 900ºC$$
$$750 \text{ kcal/kg CaO}$$
$$CaMg(CO_3)_2 + heat \rightarrow MgO + CaO + CO_2$$
$$500 - 700ºC$$
$$600 \text{ kcal/kg MgO}$$
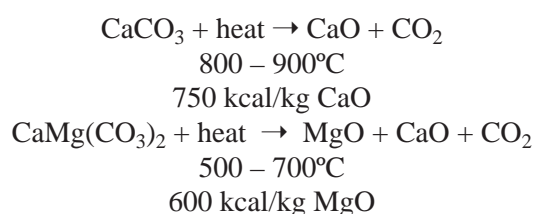
With conventional (naturally-occurring) raw materials and when producing OPC, the emissions of process CO_2 amount to about 0.55 tCO_2/t clinker produced. The process CO_2 accounts for more than 50% of total CO_2 emissions in the clinker production process.

Over the years, cement manufacturers have made efforts to reduce fuel use, make efficiency savings and use waste materials in cement production leading to decreases in mainly fuel-related CO_2 emissions per unit of product. Although many cement plants around the world still operate at well below the efficiency levels of the best available technology (which leaves considerable room for improvement) a modern cement plant achieves a relatively high energy efficiency and good CO_2 performance. The potential for further improvements is limited. To go beyond the current approaches of the cement industry, active research is being carried out to investigate technologies to reduce the CO_2 emissions of the calcination step or eliminate it altogether.

9.1 Alternative decarbonated raw materials

During the clinker production process, limestone ($CaCO_3$) is heated to a high temperature to enable a chemical reaction called 'calcination' to take place during which process CO_2 is released and calcium oxide (CaO) is formed. It is problematic to reduce the amount of CO_2 released in the calcination of limestone. However, it is possible to reduce the emissions of process CO_2 by replacing some of the limestone with a non-carbonate source of calcium.

9.1.1 Cement kiln dust (CKD)

Cement kiln dust (CKD) is a partially calcined/decarbonated material generated in the clinker-burning process and is captured by dust emissions control devices. Most plants can reuse the kiln dust by returning it to the kiln system. In some cases, reuse of CKD requires the application of sophisticated dust management techniques or process technologies. CKD typically contains alkali compounds that at certain concentrations would create kiln operational problems. Where CKD does not contain compounds at a level that affects plant operation or product quality, in dry process plants, CKD is

normally returned to the kiln feed. However, it may not be possible to recirculate CKD in a wet process plant as partially calcined dust tends to harden and cause blockages. As a solution, a few plants insufflate CKD into the burning zone of a wet process kiln. CKD has also been used as an additive in blended Portland cements (VDZ/PENTA, 2008).

Installation of dust return systems requires a capital investment that is estimated to be 2.8 \$/t clinker with an additional operating cost of about 0.10 \$/t clinker. The clinker production should increase by 2% with penalties of 21 kJ/t clinker and 1 kWh/t clinker in thermal energy and electricity consumption, respectively (Hollingshead and Venta, 2009).

9.1.2   Steel slag

Steel slag can be either crystalline or glassy depending on the rate of cooling. Quenching or rapid cooling will produce glassy slag usable as a clinker substitute, as discussed in Chapter 7. Air cooling produces crystalline slags that may be used as a partial substitute for raw materials in cement kiln feed. Steel slag contains chemical compounds such as calcium silicates, aluminates and alumino ferrites similar to the composition of cement clinker and hence is suitable as one of the raw materials. Steel slag can be fed directly to the kiln without being ground. In the kiln, steel slag begins to react with the raw materials before the sintering zone due to its relatively low melting point. Dicalcium silicate (C_2S) present in varying amounts in slag is converted into tricalcium silicate (C_3S) by combining with CaO from the raw feed. This exothermic reaction results in slag as an energy efficient and highly effective addition to the clinker manufacturing process (VDZ/PENTA, 2008).

Test results from a cement plant in the USA showed that about 78 kg of slag could provide the same amount of calcium which 91 kg or more of limestone would do, which in turn avoided the emission of 40 kgCO_2. In other words, for each tonne of steel slag used to replace limestone (in terms of calcium provided for clinker) 0.512 t less CO_2 will be emitted (VDZ/PENTA, 2008).

Depending on the composition of slag, properties of the other raw materials, and the type of clinker to be produced, steel slag can replace up to 15% of limestone in the raw meal. Implementing raw material substitution with steel slag is very simple and only minor modification is required. All that is needed is a slag hopper with a regulated withdrawal system and conveyors to a feed point leading to the kiln. For an average investment of about 0.90 \$/t clinker, and additional operating costs of about 0.10 \$/t clinker, production can be increased by 5% with a corresponding power and thermal energy savings of 3 kWh/t clinker and 63 MJ/t clinker respectively (Hollingshead and Venta, 2009). The energy savings and CO_2 emissions reduction potential using steel slag as a component in kiln feed are site specific. Nevertheless, one study estimated that for a 15% replacement of raw materials by blast furnace slag, the consumption of thermal energy can be reduced by 100 to 400 MJ/t but the consumption of electricity may increase by 0 to 2 kWh/t clinker. This may result in a decrease in direct CO_2 emissions by 0 to 117 kg CO_2/t and an increase in indirect CO_2 emissions by 0 to 2 kg CO_2/t clinker (ECRA/CSI, 2009).

9.1.3   Coal ash

Certain fly ash and boiler bottom ash can also be used as a raw material to replace a proportion of the limestone. Where a low alkali cement product is desired, the use of steel slag or coal ash can reduce the alkali content of the finished product. This may save 169 MJ/t cement by reducing the need to bypass kiln exit gases to remove alkali-rich dust. Reduction in the amount of limestone needed for clinker production can result in energy savings of 1.18 GJ/t cement. This is slightly offset by the need to dry coal ash, which may consume 74 MJ/t cement (Worrell and Galitsky, 2008). Table 21 shows the potential reductions in CO_2 emissions and thermal energy consumption by using decarbonated kiln feeds.

Table 21 Potential reductions in CO$_2$ emissions and thermal energy consumption by using decarbonated raw materials (EPA, 2010b)

	CO$_2$ emissions avoided, t calcined CO$_2$/t material	Thermal energy savings, MJ/t material
Blast furnace slag	0.35	1280
Steel slag	0.51	1850
Class C fly ash	0.20	710
Class F fly ash	0.02	81.4

The costs associated with implementing raw material substitutions are site specific. Primary capital costs are related to storage and handling systems for the materials and they have been estimated to be 0.72 $/t cement capacity (Worrell and Galitsky, 2008).

9.1.4 Calcerous oil shale

Some oil shale deposits contain calcareous material that is partially decarbonated and oil shale materials have been used in cement plants in Germany and Russia as an alternate feed stock. These shale materials have calorific value and can also be used as a fuel substitute. They can be added to calciners as a partial substitute for conventional energy sources or in an auxiliary furnace for power generation. If the shale is burnt separately, the ash can be used as a raw ingredient with a less embodied CO$_2$. When oil shale is burnt in the calciner, the organic matter responsible for energy is only 9% of the shale with the balance consisting of minerals (42.7% calcium carbonate), which substitutes for some conventional raw materials (VDZ/PENTA, 2008).

Oil shale materials can comprise as much as 8% of the raw meal. The capital investment for installation of a feed system is estimated to be 1 $/t clinker. The operating costs would increase by 0.10 $/t clinker (assuming that the source of the shale is close to the facility). This modification could reduce energy requirements by 84 MJ/t clinker and reduce CO$_2$ emissions by 0.005 kgCO$_2$/t clinker (Hollingshead and Venta, 2009).

Comments

Replacing limestone with alternative calcium-containing raw materials with less embodied CO$_2$ offers a chance to reduce emissions of both the process-related CO$_2$ and the fuel combustion related CO$_2$ in clinker production. In addition to the materials discussed above, examples of such decarbonated alternative raw materials also include concrete crusher sand, aerated concrete meal and lime residues from the sugar industry. However, the use of alternative raw materials is in general limited by their overall composition. The excess amount of silica, alumina, magnesia and sulphur in any alternative decarbonated raw materials may hinder their use at large scale. The content of volatile organic compounds or trace elements and a variable composition may cause a further restriction in some cases. Furthermore, as in the case of clinker substitution, the availability of such decarbonated raw materials is limited, restricting their widespread utilisation.

9.2 Innovative cements with low embodied CO$_2$

If somehow the calcination step could be changed or even removed altogether, it may then be possible to achieve significant further reductions in CO$_2$ emissions. This may involve taking a fresh look at the definition of cement or cementitious materials, from the point of view of their chemistry and the entire production process. Extensive research is being carried out to investigate new recipes or innovative processes for making low-carbon cements. A large number of potential OPC replacements and substitutes are currently being developed by start-up companies, universities and established cement manufacturers. The following sections provide brief discussions of some of the processes being developed and they only scratch the surface of the work being undertaken.

9.2.1 Belite clinkers

To understand the opportunities to reduce the embodied CO_2 from calcination we need to look at the modified Rankin diagram of the major oxides involved in cementitious material formation as shown in Figure 17. The majority of OPC clinker produced around the world has a lime saturation factor (LSF=CaO/($2.8SiO_2 + 1.2Al_2O_3 + 0.65Fe_2O_3$)) between 90% and 100% and a silica modulus or ratio (SM= SiO_2/($Al_2O_3 + Fe_2O_3$)) between 2.0 and 3.0 (Clark, 2010). The area of the system occupied by OPC clinker in the Rankin diagram is therefore very small.
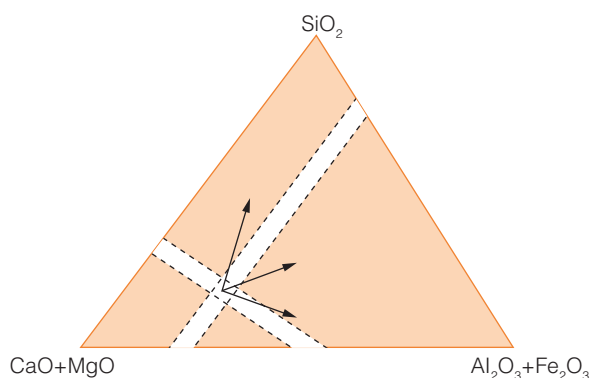
The minerals contained in the OPC clinker are silicates, aluminates or alumina ferrites of calcium, with calcium being derived almost entirely from calcium carbonate. From the calcination reaction of $CaCO_3$ shown earlier in this chapter it can be seen that for every molecule of calcium oxide in clinker one molecule of CO_2 has been emitted. The most important cementitious mineral in OPC clinker is tricalcium silicate (C_3S, also known as alite), in which three molecules of calcium oxide are combined with one of silica. Three molecules of CO_2 are therefore emitted for every molecule of the main OPC clinker mineral that is produced. Table 22 shows CO_2 emissions associated with minerals in Portland cement clinker. OPC clinker typically contains 40% to 60% by weight C_3S (ECRA/CSI, 2009, Clark, 2010). It can be seen from Table 22 that C_3S has the highest associated CO_2 emissions. These high stoichiometric CO_2 emissions associated with the production of C_3S are exacerbated by the fact that temperatures in excess of 1400ºC are required for the production of C_3S. The other

Figure 17 Modified Rankin diagram of the compositions of the major oxides contained in different types of cement (Stemmermann and others, 2010)

Table 22 CO$_2$ emissions associated with minerals in Portland cement clinker (Clark, 2010)		
Mineral	CaO, wt%	CO$_2$, wt%
C$_3$S	73.68	57.89
C$_2$S	65.12	51.16
C$_3$A	62.22	48.89
C$_4$AF	46.19	36.29

three OPC clinker minerals in Table 22, C_2S (belite), C_3A and C_4AF are themselves hydraulic and cementitious, and therefore producing clinkers with less or no C_3S can reduce the CO_2 emissions of the calcination step (Clark, 2010). This is the impetus behind research into the development of belite and other innovative cements.

Belite clinker contains no or only small amounts of C_3S but up to 90% C_2S. Belite clinkers have SLF as low as 80% and can be burnt like OPC clinker at lower temperatures around 1000ºC to 1100ºC (ECRA/CSI, 2009, Clark, 2010). As a result, fuel energy and CO_2 emissions from fuel combustion may be reduced. However, the poorer heat recovery in the cooler due to the lower clinker burning temperatures means that the associated savings in fuel energy are only about 5%. This has to be balanced against the fact that belite clinker is hard and difficult to grind and therefore requires more grinding energy (ECRA/CSI, 2009).

The low SLF of belite clinker enables the increased use of additives such as slag for clinker production and hence saves valuable natural resources (ECRA/CSI, 2009).

The major challenge of belite clinkers is the low hydraulic activity of C_2S compared to C_3S, leading to a decelerated strength development. If such cements were used in construction the construction times

would be much longer and uneconomic. The hydraulic hardening of belite cements can be improved by addition of OPC or ground alite, or doping with barium, alkali metal or phosphate ions. Super-fine grinding might render the belite cement sufficiently reactive but that would increase the energy intensity of its manufacture to uneconomic levels (ECRA/CSI, 2009, Clark, 2010).

An activated belite cement with similar 28-day strength to OPC can be produced by quench cooling the clinker. However, this approach has proved to be uneconomical because the heat of the clinker cannot be recuperated with currently known technology (ECRA/CSI, 2009, Clark, 2010).

CSA-belite cements

CSA (calcium sulpho-aluminate)-belite cements are generally made by sintering industrial wastes such as fly ash and gypsum with limestone at a temperature of 1200–1250ºC in a rotary kiln. After calcination, the clinker is ground and mixed with 35% to 70% belite and between 10% and 30% calcium ferroaluminate (Edwards, 2011)

CSA-belite cements have been commercially produced in China for over two decades. The product has similar setting characteristics to OPC but is more expensive than OPC. The CO_2 emissions from the production of CSA-belite cements are around 80% of those for OPC (Edwards, 2011).

9.2.2 Geopolymers

Geopolymers are two-component binders consisting of a reactive solid component and an alkaline activator. Geopolymers are another class of cements based on pozzolans (natural or man-made). They differ from conventional pozzolanic cements because the pozzolanic materials and latent hydraulic materials present in geopolymers are not activated by cement clinker but instead make use of sodium hydroxide or sodium silicates (ECRA/CSI, 2009; WWF, 2008).

Chemically geopolymers can be divided into two groups depending on their composition: materials containing mainly Al and Si such as metakaolin and those containing mainly Ca and Si such as steel slag. The former form complex three-dimensional poly-aluminosilicate networks upon activation leading to high compressive strength which has been shown to increase over a period of many years for some systems. Geopolymeric binders of the latter group form C-S-H- and C-A-H-phases beside the aluminosilicate network causing wide variations in quality (ECRA/CSI, 2009; Edwards, 2011).

Other advantages of alkali-activated binders include higher early strength, high resistance to chemical attack, good resistance to a range of temperatures and low CO_2 emissions (Edwards, 2011). The CO_2 emissions from the production of geopolumers may be lower than those of OPC by up to 80%, provided the pozzolan itself does not have to be specially produced (WWF, 2008; Edwards, 2011).

Until now, geopolymers have been produced only for demonstration purposes and have only been used in applications such as paving, rather than structural applications. The main technical challenge seems to be maintaining a stable and defined product quality and concrete performance. A first industrial plant is being built in Australia and the expected CO_2 emissions are 300 kgCO_2/t product. However, the emission figure here has not taken into account the CO_2 emissions from the production of activators (ECRA/CSI, 2009). The availability of suitable pozzolanic materials may be a problem in many locations, and the world supply of the sodium hydroxides or silicates required as activators is currently insufficient to meet the demand if this technology were to be more widely used (WWF, 2008).

9.2.3 Calera cement

Calera is a California-base company and it is developing a process to convert CO_2 into cementitious

materials. In this radically different process, flue gas from power plant chimneys passes through a stream of water with high concentrations of calcium and magnesium salts. The calcium and magnesium ions in the water react with CO_2 to form insoluble salts which precipitate out of solution and can be processed into cement (Edwards, 2011).

The major environmental advantage of the Calera process is that it can capture CO_2 from industrial off-gas, such as that of conventional power plants, and turn it into a useful product. The company claims that for every tonne of cement produced using Calera process, emissions of half a tonne of CO_2 may be avoided (McKenna, 2010). Seawater contains calcium and magnesium and is ideal for the Calera process. The process results in a seawater stream that is stripped of calcium and magnesium and can be used for desalinisation to make clean water, but it is also safe to be discharged back into the sea. For plants located in areas where seawater is not available, the water used for the process could be sourced from a number of industrial processes. The Calera process can be attached to power plants, steel mills and other industrial processes as a CCS unit. When attached to a coal-fired power plant, fly ash can be used as a source of alkalinity and cations for the Calera cement.

Calera so far has provided little factual information about how the process actually works. The energy requirement of, and net CO_2 emissions saved by, the process are unknown. While the Calera process provides an innovative approach to production of low-carbon cement, it has yet to be shown that the process is actually technically and economically viable, especially at large scale.

9.2.4 Magnesium cement

Magnesium cements are based on reactive MgO instead of CaO. The reactive magnesium is produced by calcination of $MgCO_3$ at temperatures in the region of 650ºC to 750ºC, significantly lower than that of $CaCO_3$, to produce a highly reactive MgO. When mixed with water in a mortar or concrete the reactive magnesia hydrates consume significant excess water to form brucite hydrates ($Mg(OH)_2$). These brucite hydrates hold water between layers of brucite in such a way that it is available for the later, more complete hydration of the cement clinker minerals, which leads to higher ultimate strength. Durability of the mortar or concrete is also improved due to the reduced permeability (Clark, 2010).

The problem with magnesium in OPC clinker is that it is subjected to the temperatures in excess of 1400ºC in the burning zone of the kiln and is therefore dead-burned and unreactive resulting in the hydration of magnesium in cement clinker being very slow. The slow and expansive hydration of MgO can lead to cracking of concrete as the MgO hydration may take place well after the concrete has set and hardened. As a result, international standards for cement limit the allowable MgO content to 4%, 5% or 6% dependent on the country where the standards apply. However, magnesium cements contain reactive MgO that hydrate forming brucite before the mortar or concrete has set and hardened and therefore there will be no long-term expansive hydration.

It has been claimed that magnesium cements could be manufactured with greatly reduced CO_2 emissions compared to OPC, and that concretes made from such cements would absorb atmospheric CO_2 faster even than concretes made from OPC (WWF, 2008). Several such cements have been developed by different companies.

TecEco cements

An Australian company TecEco Pty Ltd has developed and marketed alternative cements based on reactive magnesium. In its Tec-Cements 5% to 20% of OPC clinker is replaced by reactive magnesium oxide whilst 20% to 95% of OPC clinker is substituted in its Eco-Cement (Clark, 2010).

The decarbonisation reaction that converts MgCO to MgO requires significantly less energy compared to limestone leading to a reduction in fuel consumption and hence lower costs and CO_2 emissions. The lower kiln temperatures also make it easier to use alternative fuel sources. In addition, TecEco

claims that Eco-Cement is more porous than OPC enabling it to absorb atmospheric CO_2 rapidly once it is set. The finished product is comparable in many respects to OPC in terms of strength and chemical resistence but has better resistence to chlorides and sulphates, and lower shrinkage than OPC (Edwards, 2011).

Novacem cement

Novacem is a UK-based company and it is developing a 'green' cement that absorbs CO_2 instead of emitting it. The cement is based on magnesium oxide (MgO) and hydrated magnesium carbonates. Magnesium silicates are used as starting material instead of magnesium carbonate. The production process uses accelerated carbonation of magnesium silicates under elevated temperature (180ºC) and pressure (150 bar/15 MPa). The carbonates produced then undergo a calcination process at relatively low temperatures (700ºC) to produce MgO, with the CO_2 generated being recycled back in the process. The use of magnesium silicates eliminates the CO_2 emissions from raw materials processing. In addition, the low temperatures required allow use of fuels with low energy content or carbon intensity such as biomass, thus further reducing carbon emissions. Furthermore, production of the carbonates absorbs CO_2. The $MgCO_3$ is produced by carbonating part of the manufactured MgO using atmospheric/industrial CO_2. Overall, the production process to make 1 tonne of Novacem cement absorbs up to 100 kg more CO_2 than it emits, making it a carbon negative product (http://novacem.com/technology/novacem-technology/).

Novacem cement is composed of between 50% and 80% magnesium oxide and hydrated magnesium carbonates, which allow rapid strength development in applications where CO_2 is not readily available such as in underwater applications. Novacem has joined up with Liang O'Rourke, a construction firm, to produce masonry blocks, a building material that has relatively low performance. The cement is still in development and if the new cement shows itself to be a strong and safe construction material, it could be adopted for a wider range of uses (McKenna, 2010; Edwards, 2011).

9.2.5   Carbon concrete

Carbon concrete is not a mineral-based product but may still find use in applications where OPC may have been used. It is especially attractive for special applications like heavy industrial roads or saltwater applications. It is a thermoplastic binder which, when mixed with aggregates, sand and filler, forms carbon concrete that combines a strength close to concrete with an enhanced flexibility and an extremely good resistance to wearing. As such, less material is needed for a similar application (WWF, 2008).

Carbon concrete is produced from the sludge left over after oil refining, a by-product that has usually simply been burnt at refineries in order to get around waste-disposal legislation. This is a process that produces CO_2 with no benefits (Edwards, 2011).

C-Fix is a such product. C-Fix is produced by C-Fix bv, a joint venture between Royal Dutch/Shell Group and UKM Ltd. Instead of burning the heavy by-product of oil refineries, C-Fix bv has developed a process in which the refinery by-product is heated to around 200ºC and mixed with aggregates and sand. The company claims that using 1 tonne of C-Fix prevents the emissions of 2.5 tCO_2 when replacing OPC as a binder in concrete mix. Another environmental benefit of carbon concrete is that its production does not consume any water (Edwards, 2011).

C-fix is currently sold mainly as an industrial flooring material and it has also found use in sea-wall defence and as sewage pipes (Edwards, 2011).

9.2.6   Celitement

Celitement relies on the traditional ingredients of cement, but uses significantly less limestone than

OPC resulting in reductions in energy use and associated costs and CO_2 emissions. Celitement is made by heating in an autoclave, under a saturated water vapour partial pressure, a mixture of calcium and a number of different silicates with a molar ratio of 0.5 to 2. The temperature in the autoclave is between 150ºC and 300ºC. During this process calcium silicate-hydrates are formed, which when mixed with further silicates and milled in a reactive mill produce hydraulically active calcium hydrosilicates – Celitement (http://www.celitement.com).

Additives can be used to control the hydration with water and the quality of the final product. Pozzolans and/or OPC clinker can be added to the Celitement as well, which gives a product that has properties similar to OPC and hence can be easily handled by established methods. Although the CaO used to make Celitement has to be formed from limestone, the proportion of limestone used is clearly much lower compared to OPC. As a result, emissions of both process related CO_2 and fuel combustion related CO_2 are reduced. The overall primary energy consumption is estimated to be 3150 MJ/t of Celitement produced compared to the aveage value of 4360 MJ/t clinker produced in a conventional cement kiln. The total CO_2 emissions from the production of lime-rich Celitement (by intergrinding α-$Ca_2[HSiO_4]OH$ and quartz sand in a ratio of 1:1 by weight) are estimated to be 483 $kgCO_2$/t Celitement, which is about half of the emissions from clinker production. Celitement has properties similar to OPC and it has lower porosity making it durable and resistant to chemical attack (Stemmermann and others, 2010). The construction of a Celitement pilot plant in Germany began in August 2010.

9.2.7   Calcium-aluminate cements

From Table 22 (*see* page 72) one can see that cements based on calcium aluminates and calcium aluminoferrites have lower associate process CO_2 emissions. Calcium aluminate cements are well known and occupy a niche position in the cement industry. They are produced from calcium carbonate and bauxite and composed of CA, $C_{12}A_7$, and C_3A. The bauxite raw material often contains high concentrations of Fe_2O_3 and therefore calcium aluminoferrite is also often present. All these components have lower embodied CO_2 levels compared to C_3S in OPC (Clark, 2010).

Calcium aluminate cements exhibit very high strength growth-achieving compressive strengths equivalent to the 28-day strength of OPC within one to two days. However, the hydration products of the main calcium monoaluminate, CA, are dependent on the curing temperature and conditions. In a warm and humid environment, the hydration products tend to slowly lose water leading to a gradual loss of mass and strength (Clark, 2010). Therefore, calcium aluminate cements are not suitable for use in construction. Furthermore, the use of bauxite as raw material makes these cements expensive.

9.3   Comments

In addition to those discussed above, there are a large number of innovative cements with low embodied CO_2 that may potentially replace or substitute OPC. Some of them have already found use in certain applications or in a position to make full production a reality, whilst the others are still in development. Individually, these products may not be able to cover the whole range of applications of the traditional OPC but together they may cover the full range and even offer better performance in certain applications.

A switch to innovative low-carbon cements would probably mean a shift away from the OPC clinker. OPC is cheap to produce and incredibly strong with well-established production and supply chains and markets. Any low-carbon alternative would need to have similar properties and performance with a cost comparable to that of OPC to be able to replace an appreciable amount of OPC. Unfortunately, any low-carbon alternative to OPC will be expensive initially. In most cases, modification to existing plants or construction of a new plant is required for production of such innovative cement, which

requires a significant capital investment. Its properties and performance may be unfamiliar to users. It will need to develop its supply chain and may have to undergo the process of being standardised if it is to become a commodity. This means that there will be a risk associated with the attempts to market any of the innovative low-carbon cement products that it may not pay off, even if it is a perfectly chemically sound option. Even if the possible reduction in CO_2 emissions using innovative cement materials is huge, the chances are that without measures to help them emerge, priority will be given in the short term to conventional abatement measures such as energy efficiency improvement, alterative fuel, clinker substitutes. Unless a legal constraint and/or a strong and effective market for emission trading are established making CO_2 emissions reductions financially rewarding, a shift from OPC to low-carbon cement materials is unlikely to happen.

10 Conclusions

World cement production has been increasing steadily in the past. Due to the unique nature of cement manufacturing, cement production is energy- and carbon-intensive, making it a key source of CO_2 emissions. There are a large number of technologies and various non-technical measures available to reduce CO_2 emissions from cement production.

10.1 Improving thermal energy efficiency

Clinker production is the most energy-intensive step, accounting for around 80% of the energy used in cement manufacturing. The fuel demand for clinker production of individual plants depends on the kiln technologies used and the kiln size. Today's state-of-the-art cement kiln process uses the dry kiln processes with multistage cyclone preheaters with an integral pre-calciner and this process is the most energy efficient. Whenever possible, the cement manufacturers should always adapt to the best available technologies in cement production. Over the past two decades, cement manufacturers have achieved greater energy efficiencies by closing small and inefficient plants and modernising others. This has resulted in a significant reduction in unit-base CO_2 emissions in cement production. Improving energy efficiencies can not only lead to considerable CO_2 emissions reductions in cement production but can also provide a cost advantage to cement manufacturers through lower energy costs. For old cement plants a significant decrease in specific energy consumption can be achieved through major retrofits. However, such retrofits require high capital investment. In most cases, converting an old kiln to a modern kiln is not considered economically feasible unless the old kiln to be replaced is at the end of its life. Apart from a major upgrade of an existing cement kiln system, other measures such as reducing the heat loss from the kiln system, improving kiln combustion system and optimising the kiln operation using process control and management system, and waste heat recovering for power generation can all contribute to increased energy efficiencies and lower CO_2 emissions.

10.2 Improving electrical energy efficiency

Cement manufacturing involves complex processes and equipment. Energy efficiency improvements can be achieved through several approaches such as implementing best available technologies and non-technical measures. Grinding processes are the major power consumers in cement plants and hence grinding technologies have a considerable impact on total electric energy demand. Modern grinding technologies can reduce the electricity demand of the raw and finishing grinding operation as well as that of coal milling for fuel preparation, leading to reductions in indirect CO_2 emissions.

In a cement plant between 500 and 700 motors are used to drive the rotary kiln, the fans, grinding mills and other equipment. Using modern highly-efficient motors or improving the efficiency of the existing motor system can result in a significant reduction in electricity use and related indirect CO_2 emissions. A reduction in the power demand of a cement plant can also be achieved by measures such as improving raw material blending/homogenising, using high efficiency classifiers/separators, efficient transport systems and fans, reducing pressure losses in cyclone preheaters and implementing a slip power recovery system. All of these options are off-the-shelf technology and most can be implemented easily.

10.3 Alternative fuels

Coal, the most carbon-intensive fossil fuel, is the most widely used fuel in the cement industry. Approximately 40% of the CO_2 released during cement manufacturing is the result of fossil fuel combustion in the kiln. Therefore, switching from coal to a lower carbon content fuel such as natural

gas and oil will reduce the fuel combustion related CO_2 emissions significantly. However, the higher prices of natural gas and oil, the availability and security of the fuel supply are the major barriers to fuel switching.

Replacing fossil fuel with biomass saves energy and natural resources as well as reducing CO_2 emissions. However, there are several technical challenges and some financial barriers to the use of biomass fuels in cement kilns. In addition, the availability and price of biomass fuels may also become a limiting factor to their wider application.

The use of wastes as alternative fuels in cement kilns has a number of potential benefits such as the recovery of the energy content of waste, conservation of non-renewable fossil fuels, reduction of overall CO_2 emissions, lowering cement production cost and the use of existing technology to safely treat hazardous wastes, eliminating disposal of such wastes through incineration or landfill. The CO_2 emissions reduction potential of substitution of conventional fuels with alternative fuels depends on the CO_2 emission factors related to the energy content of the alternative fuels compared with that of conventional fuels, and the substitution ratio. However, the CO_2 savings from substitution of conventional fossil fuel with waste derived fuel (WDF) go beyond the pure lower emission factors. Cement kilns are well suited for co-processing a wide range of waste materials. No major technical changes are needed when replacing conventional fossil fuel with WDF. The limiting factors are non-technical and lie in areas such as availability and supply of WDF, permitting procedures, economics of using WDF, and social acceptance.

10.4 Clinker substitution

Clinker substitution is the most cost effective way to reduce CO_2 emissions from cement production and has other environmental benefits. Replacing a proportion of the clinker in the cement with other cementitious materials has already been widely practised for many years. The supplementary materials that can be used as clinker substitutes include GGBFS, fly ashes from coal combustion, and other natural and manufactured pozzolans. Many types of blended and composite cement can be produced depending on the supplementary material used and the clinker ratio.

The thermal energy consumption of the kiln decreases with the increased ratio of clinker substitutes in the blended cement due to the reduced clinker produced. The overall power consumption may be slightly lower due to the better grindability of most clinker substituting materials compared to the clinker replaced (except for GGBFS). The reduced thermal energy requirements and possibly lower power consumption result in decreases in both direct and indirect CO_2 emissions in clinker production process and in associated costs.

Clinker substitution is the least costly CO_2 reduction method for the cement industry and requires low capital costs. Technically, further reduction of clinker ratios to values lower than the current global average are possible but there are issues limiting the implementation of clinker substitution. First is availability. Other limiting factors include properties and price of the material, intended application of the cement, national standards and market acceptance.

10.5 Carbon capture

The carbon capture technologies potentially applicable for cement manufacture are post-combustion and oxyfuel combustion capture.

Post-combustion capture
Post-combustion capture can be adapted to any combustion or CO_2 producing process. It does not require fundamental changes in the clinker making process and is therefore suitable for new kilns and

in particular for retrofits. It has been estimated that up to 95% of the CO_2 emissions from a cement plant could be avoided if post-combustion capture is implemented.

There are several technical approaches to the capture of CO_2 from flue gas: absorption processes, adsorption processes, membrane separation and cryogenic separation processes. Some of the chemical and/or physical absorption processes are now commercially available with the chemical absorption process being the leading technology currently used for post-combustion CO_2 capture. The adsorption process is not yet a mature technology for potential application at cement kilns. However, the carbonate looping process using CaO as sorbent, when properly developed, may be suitable for CO_2 capture in a cement plant. The membrane and cryogenic separation processes, although some have been successfully used in other industrial processes for gas separation, are still under development and are not yet commercially available for CO_2 capture at large scale power or cement plants. More research is needed in this area.

Oxyfuel combustion

In oxyfuel combustion, fuel is burned in pure O_2 instead of air and this results in a flue gas that is composed mainly of CO_2 (>80%) and water vapour, which is easily separated at low cost by the condensation process, eliminating the need for costly post-combustion capture systems. However, the major cost and energy penalty of post-combustion processes is traded here for the costly and energy-intensive oxygen production. In addition, to introduce oxyfuel combustion technology into an existing cement plant is extremely challenging. The production of oxygen is a key step in an oxyfuel combustion system. Typically, cryogenic air separation is used but ion transport membranes and chemical-looping combustion are emerging as alternative technologies for oxygen supply, which may reduce the costs of oxygen production.

Although carbon capture technologies exist, scaling up these existing processes and integrating them with cement kilns poses technical, economic and regulatory challenges. Currently, the costs of CO_2 capture are high which could inhibit widespread commercial deployment of CCS.

10.6 Low-carbon cement

With traditional limestone raw material and when producing OPC, the emissions of process CO_2 account for more than 50% of total CO_2 emissions in the clinker production process. It is possible to reduce the process CO_2 emissions by replacing limestone with raw materials with low embodied CO_2, or replace OPC with innovative low-carbon cements.

Replacing limestone with alternative calcium containing raw materials with less embodied CO_2 offers a chance to reduce emissions of both the process related CO_2 and the fuel combustion related CO_2 in the clinker production. Examples of such decarbonated alternative raw materials include CKD, steel slag, fly ash and other pozzolanic materials, and concrete wastes. Such practice's can be found in several countries. Implementing raw material substitution is fairly simple technically and requires low capital investments but the application is subject to the availability of the substituting materials.

Extensive research is being carried out to investigate new recipes or innovative processes for making low-carbon cements. A large number of innovative low-carbon cements that may potentially replace or substitute OPC have been developed or are in development. In many cases, the production of the innovative cements involve chemistry that is completely different from that of OPC production. They offer opportunities to significantly reduce CO_2 emissions from cement production. However, due to the well established production and supply chain and the low prices of OPC cement, a significant shift from OPC to innovative low-carbon cement materials is unlikely to happen unless a legal constraint and/or a strong and effective market for emissions trading are established to make CO_2 savings financially rewarding.

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