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CO$_2$ Capture in the Cement Industry

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Abstract

Modern cement plants have high energy efficiencies and the scope to reduce CO$_2$ emissions by further efficiency improvements is small. One of the few ways of greatly reducing CO$_2$ production from cement production is CO$_2$ capture and storage (CCS). This paper summarises a study which assessed the technologies that could be used for CO$_2$ capture in cement plants, their costs, and barriers to their use. The work covered new-build cement plants with post-combustion and oxy-combustion CO$_2$ capture. The basis of the study was a 5-stage preheater with precalciner dry process cement plant with a cement output of 1 Mt/y located in NE Scotland, UK. Process Flow Diagrams (PFDs) and heat and mass balance calculations for both options were developed. The plant costs were estimated and the costs per tonne of CO$_2$ emissions avoided and per tonne of cement product determined.
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Keywords: cement; CO$_2$ capture and storage (CCS); post-combustion; oxy-combustion; costs; performance.

1. Introduction

The cement industry is one of the world's largest industrial sources of CO$_2$ emissions, accounting for 1.8 Gt/y in 2005 [1]. Over the years the cement industry has substantially reduced emissions of CO$_2$ per tonne of cement by improved energy efficiency, replacing fossil fuels with wastes which may be regarded as 'carbon neutral' and increasing the cement: clinker ratio by increasing the use of additives. The scope for further reductions by these means is becoming limited but there is an increasing need to reduce CO$_2$ emissions to avoid contributing to anthropogenic climate change. CO$_2$ capture and storage (CCS) presents one of the few opportunities to make further major reductions in emissions. In many ways the cement industry represents a good opportunity for CCS, because cement plants are relatively large point sources of CO$_2$, the CO$_2$ concentration in cement plant flue gas is relatively high and over 60% of total CO$_2$ emissions from a modern cement plant are from mineral decomposition where the resulting CO$_2$ emissions cannot be avoided by use of alternative energy sources.

The IEA Greenhouse Gas R&D Programme commissioned a study to assess the technologies that could be used to capture CO$_2$ in cement plants and their performances and costs. The study was undertaken by Mott MacDonald

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with input from Whitehopleman and the British Cement Association. This paper describes the technical and economic assessment of employing post-combustion CO_2 capture and oxy-combustion CO_2 capture at modern cement plants. Pre-combustion capture was not evaluated in detail in this study, mainly because it would only be able to capture the fuel-derived CO_2, not the larger quantity of CO_2 from decomposition of carbonate minerals.

The technical and economic assessments were based on dry-feed cement plants in NE Scotland, UK with 5 stages of preheating, producing 1 million tonnes/year of cement (910,000 t/y of clinker). The study was based on existing CO_2 capture technologies or technologies which could be developed for use in cement plants in the near future with moderate risk. It should be recognised that further development of technologies may significantly increase the fraction of CO_2 captured and reduce the cost per tonne of CO_2. Costs of cement production and CO_2 capture were calculated assuming a 10% annual discount rate in constant money values, a 25 year plant life, 90% load factor, a coal price of €2.51/GJ (LHV basis) and a petroleum coke price of €2.34/GJ (LHV basis). A full list of the economic criteria used is given in the main report [2].

2. Cement Plant Without CO₂ Capture

Figure 1 shows the process flow arrangement for a typical modern cement plant without CO_2 capture as used as the base case in this study.
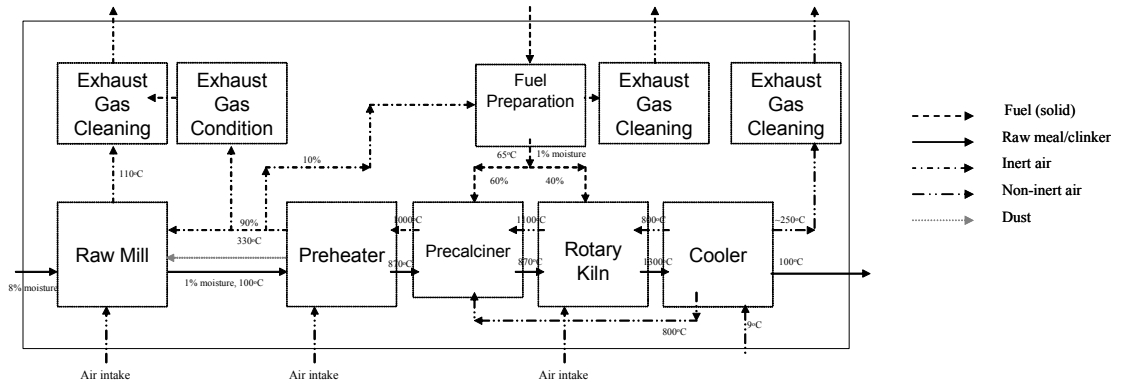

Figure 1 Schematic of cement plant without CO₂ capture

Additional downstream processes, not shown on Figure 1, include cement milling, packing and loading. Common issues relating to the addition of CO_2 capture to a cement plant include:

- **Additional Power Requirements.** There will be additional power requirements for the operation of the post-combustion capture plant and the CO_2 compression plant. The power requirement for compression of CO_2 to 110 bara has been reported to be around 0.146 kWh/kgCO_2 [3].
- **Heat Integration.** Although the cement process has been highly optimised already, both post-combustion and oxy-combustion capture offer potential opportunities to maximise performance through heat recovery from the CO_2 compression system.

3. Cement Plant With Post-combustion CO₂ Capture

Post-combustion CO_2 capture has been widely studied for application at coal- or gas- fired power stations (e.g. [4]) but there are few studies that have examined its application at cement plants. This study was based on the use of post-combustion amine scrubbing using monoethanolamine (MEA). A typical cement plant operates in such a way that will allow the incorporation of the capture equipment with limited modifications to the existing plant. However, the following issues must be considered:
- **Sulphur Dioxide (SO₂).** The concentration of SO_2 in the flue gas from the cement process is important for post-combustion capture with amines as amines react with acidic compounds to form salts that will not

dissociate in the amine stripping system. It is reported that the SO_2 concentration in the inlet to the amine absorption process should be restricted to approximately 10 ppmv [@ 6% O_2] [5]. The SO_2 concentration in the flue gas from a cement plant is highly dependant on the sulphide concentration in the raw meal used.

- **Nitrogen Dioxide (NO_2).** NO_x within the flue gas is problematic for MEA absorption systems as this results in solvent degradation. In particular, NO_2 reacts to form heat stable salts [4]. NO_x emissions associated with cement kilns vary generally between <200 and 3000 mg/Nm^3 [6]. However, typically less than 10% of the NO_x is NO_2 with the large majority being NO [7].
- **Dust.** The cement process produces significant quantities, around 3000 mg/Nm^3 [6], of dust in the flue gas. The dust is generally removed by electrostatic precipitators (ESPs) or bag filters. The presence of dust reduces the efficiency of the amine absorption process and it is understood that to operate post-combustion capture economically the dust level must be below 15 mg/Nm^3 [5].
- **Additional Steam Requirements.** One of the major issues with using MEA CO_2 capture is the large steam requirement. The steam conditions required are approximately 3.5 bara and 140-150ºC.
- **Reducing Conditions.** It is recognised that the clinker must not be generated in reducing conditions and that an excess of O_2 is maintained in the process. The O_2 concentration is required to be >2% (w/w) in the preheater, precalciner and the kiln. The O_2 content required for CO_2 absorption in MEA is >1.5% (v/v) [5].
- **Heat Reduction for MEA Absorption.** The flue gas leaves from the cement process at the raw mill at approximately 110ºC. This must be cooled to approximately 50ºC to meet the ideal temperature for CO_2 absorption with MEA. This cooling can take place in the Flue Gas Desulphurisation (FGD) system.
- **Other Gases.** Hydrochloric acid can be present in small quantities within cement flue gases; typical concentrations are around 8 mg/Nm^3 [7]. The presence of any acidic components will reduce the efficiency of the MEA absorption process.

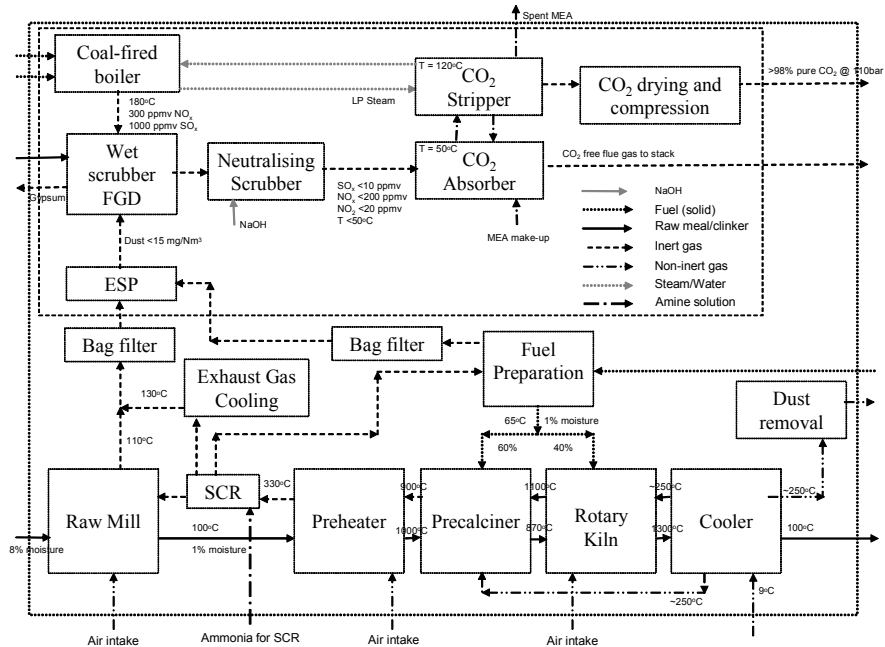Figure 2 shows the conceptual process flow arrangement selected for this particular study.

Figure 2 Schematic of cement plant with post-combustion CO_2 capture

There are five key features that distinguish the process from a conventional cement plant. These are:

- An SCR unit is fitted between the preheater and the raw mill for NO_x abatement [8].
- A wet limestone FGD unit is fitted to remove SO_x from the flue gas stream.
- CO_2 capture equipment based on MEA amine solvent separation is installed.
- A coal-fired CHP plant is installed to generate the low pressure steam for MEA stripping and to provide the additional electrical power for the operation of the amine absorption and the compressor plant. The CO_2 from this process will also be captured and will mix with the cement plant flue gas before the wet limestone FGD unit.
- The net CO_2 product is compressed, dried and further compressed to pipeline pressures of 110 bara.

4. Cement Plant With Oxy-combustion CO_2 Capture

A small number of researchers have reported the possibility of using oxy-combustion CO_2 capture at cement plants (e.g. [9]). The major technical issues associated with the oxy-combustion cement production process are discussed below. It was noted that many of the issues are considered topics for fundamental research and were beyond the scope of this study. Although the feasibility of an oxy-combustion cement process remains to be proven, none of the issues identified was considered a "show-stopper" at the time of writing this paper. The major technical issues are:

- **Flame Temperatures and Dilution.** The oxy-combustion process is based on excluding the inert components of air from the combustion process. Flame temperatures in excess of 3500ºC can be achieved in oxygen combustion. This is too hot for normal operation so it is therefore essential that a proportion of the CO_2-rich flue gases are recycled back to the combustion zone to provide the necessary dilution.
- **Heat Transfer Characteristics.** The radiant heat fluxes and convective heat transfer performance of the combustion chamber are a function of the gas composition in the chamber. Changing the atmosphere within the combustion chamber will have a significant effect on the heat transfer characteristics.
- **Feed Lifting.** It has been reported [10] that nitrogen ballast in the exhaust gases from the kiln plays an important role in lifting the feed between the cyclone stages in the suspension preheater of a modern cement kiln. CO_2 is a denser gas than nitrogen and should be more effective in this feed lifting role within the suspension preheater.
- **Wear and Tear.** Due to the higher temperatures it is generally understood that cement kiln wall deterioration will increase at higher oxygen concentrations. Hence, there is a balance between achieving the high temperatures for the cement production process and having to replace the kiln wall lining.
- **Process Chemistry.** Research is on-going to determine whether the clinker formation in a different atmosphere will still generate a useful product.
- **Air Dilution.** Significant air in-leaks occur in the raw mill, preheater and kiln. Excessive air in-leaks will result in contamination of the CO_2-rich exhaust gas. These contaminants will require removal and will increase the costs of operating an oxy-combustion process.
- **Flue Gas Clean-up.** Depending on the final storage location of the CO_2 the gas will require some clean-up to remove water vapour, nitrogen, argon, NO_x or SO_x.
- **Air Separation Unit (ASU).** An ASU will be required to deliver oxygen to the oxy-combustion process. This will require increase the electricity demand of the plant compared with a conventional cement plant. The power required by a cryogenic oxygen plant is typically in the range 200-240 kWh/tO_2 [11].
- **Reducing Conditions.** It is generally considered that the oxygen concentration in the clinker production process should be maintained >2% (w/w).
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Fuel is fed to two places in a modern cement plant: the precalciner, which helps to preheat the feedstock and calcine the raw material and the high temperature kiln where cement clinker is produced. Most (up to 95%) of the CO_2 is normally released from the limestone raw material in the preheaters and precalciner. Figure 3 shows the conceptual process flow arrangement selected for this particular study.
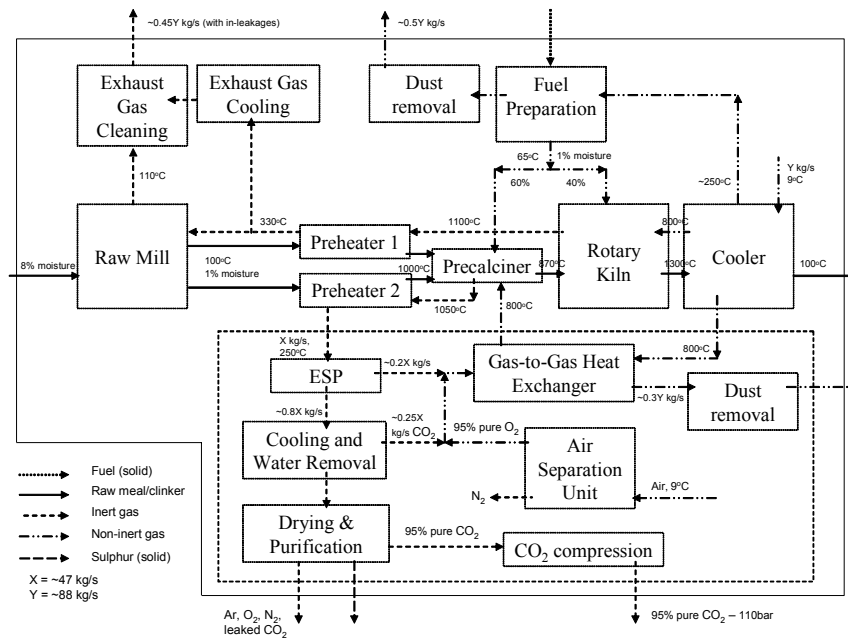
Figure 3 Schematic of cement plant with oxy-combustion CO$_2$ capture

   This scheme involves oxy-combustion of the precalciner but air combustion of the kiln and was chosen as it minimises the possible impact of a high-CO$_2$ atmosphere on the clinker production processes which occur in the kiln and minimises the impact of air in-leakage. Further R&D may show that cement kilns could be successfully operated with a high CO$_2$ atmosphere and in-leakage could be greatly reduced. If so, oxy-combustion of the kiln as well as the precalciner could be feasible.   There are three key features that distinguish the process from a conventional cement plant. These are:

1. The combustion air for the precalciner is separated prior to the precalciner in an ASU. The oxygen from the ASU (95 mol% O$_2$ with 2 mol% N$_2$ and 3 mol% Ar) is supplied to the precalciner only.
2. Around 50% of the precalciner exhaust gases are recirculated back to the precalciner burners to provide the ballasting effect which is carried out by the atmospheric nitrogen in a conventional system.
3. The net flue gas from the precalciner is cooled and passed to the CO$_2$ compression and inerts separation plant. The net product is compressed, dried, the inerts separated and the pure CO$_2$ is further compressed to pipeline pressure of 110 bara.

5. Performance and Costs of Cement Plants with CO$_2$ Capture

Steady state mass and energy balances of the processes were developed. Each individual process unit was modelled with the mass flows into and out of each process unit calculated based on simple performance equations derived from typical industry data or parameters. The energy flows were calculated using the basic thermodynamic properties of the components. The estimated performances of cement plants with and without CO$_2$ capture are summarised in Table 1.

Table 1 Summary of Cement Plant Performance With and Without CO_2 Capture

	Unit	Base case (no capture)	Post combustion capture	Oxy-combustion
Fuel and power				
Coal feed	kt/y	63.3	291.6	72.1
Petroleum coke feed	kt/y	32.9	32.9	27.1
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	kt/y	-	1067.7	465.0
CO_2 emitted on-site	kt/y	728.4	188.4	282.9
CO_2 emissions avoided at the cement	kt/y	-	540.0[a]	445.6[a]
Plant	%	-	74	61
CO_2 associated with power import/export	kt/y	42.0	-11.8	90.8
Overall net CO_2 emissions	kt/y	770.4	176.6	373.7
CO_2 emissions avoided, including power	kt/y	-	593.8	396.8
import and export	%	-	77	52

[a] The CO_2 emissions avoided are the emissions of the base case plant without capture minus the emissions of the plant with CO_2 capture.

The costs of plants with and without capture are summarised in Table 2. The costs per tonne of CO_2 emissions avoided take into account the emissions associated with imported and exported power.

Table 2 Summary of Cement Plant Costs With and Without CO_2 Capture

	Unit	Base case (no capture)	Post combustion capture	Oxy-combustion
Capital cost[a]	€M	263	558	327
Operating costs				
Fuel	€M/y	6.7	21.5	6.9
Power	€M/y	4.0	-1.1	8.7
Other variable operating costs	€M/y	6.1	10.6	6.4
Fixed operating costs	€M/y	19.1	35.3	22.8
Capital charges	€M/y	29.7	63.1	36.9
Total costs	€M/y	65.6	129.4	81.6
Cement production cost	€/t	65.6	129.4	81.6
CO_2 abatement costs				
Cost per tonne of cement product	€/t	-	63.8	16.0
Cost per tonne of CO_2 captured	€/t	-	59.6	34.3
Cost per tonne of CO_2 emissions avoided	€/t	-	107.4	40.2

[a] Note that the capital costs include miscellaneous owners' costs but exclude interest during construction, although this is taken into account in the calculation of overall production costs.

5.2   Post-combustion capture

The CO_2 emissions avoidance at the cement plant site is 74% but taking into account CO_2 avoided because of electricity exports at low carbon intensity the emissions avoidance increases to 77%. This could be increased to 93% if the percentage capture was increased to 95%. The cost of CO_2 emissions avoidance is high at €107/t. The high concentration of CO_2 in the flue gas of a cement plant compared to that of a coal or gas fired power plant reduces the size of the absorber tower and associated ducts, fans etc. However, this is more than offset by lower economies of scale, the need to include FGD, which is normally already included in most power plants without CO_2 capture but not in most cement plants, and the relatively high costs of providing steam for solvent regeneration from a modest-sized CHP plant.

5.2 Oxy-combustion

Oxy-combustion in just the precalciner avoids 61% of the CO_2 produced at the cement plant. Oxy-combustion involves a significant increase in the on-site power consumption, mainly for oxygen production and CO_2 compression and purification. Taking into account CO_2 emitted during generation of this power, the overall reduction in CO_2 emissions is 52%. If the imported power was generated in power plants with low CO_2 emissions the overall avoidance of CO_2 emissions would be close to the on-site emissions avoidance. Oxy-combustion of the kiln as well as the precalciner could increase the on-site CO_2 avoidance to close to 100% but this would involve greater technical uncertainties, as described earlier.

The cost of CO_2 emissions avoidance is €40/t, substantially lower than the cost of post combustion capture. Oxy-combustion is particularly suitable for cement plants because oxygen only needs to be provided for the CO_2 that originates from fuel combustion. No oxygen needs to be provided for the CO_2 from mineral decomposition.

5.3 Comparison with CO_2 capture in power generation

The costs of CO_2 capture in cement plants need to be viewed in the context of the costs of CO_2 abatement in other energy sectors. IEA GHG published studies on post-combustion and oxy-combustion capture of CO_2 in power generation in 2004-2005 [3, 4]. After adjusting for inflation the cost of post-combustion capture in a coal fired power plant is estimated by IEA GHG [2] to be €39/t of CO_2 avoided, which is similar to the cost of oxy-combustion at a European cement plant but less than the cost of post-combustion capture.

Cement plants normally produce smaller quantities of CO_2 than modern coal fired power plants. For example, a modern 1000 MW coal fired power plant operating at base load with 85% CO_2 capture would capture about 6 Mt of CO_2/year compared to 0.5-1.1 Mt/y of CO_2 for the European cement plants and 1.4-3.3 Mt/y for the Asian plants in this study. Cement plants with CO_2 capture should if possible be located close to power plants or other industrial plants with CO_2 capture to obtain economies of scale in CO_2 transportation.

5.4 Sensitivities

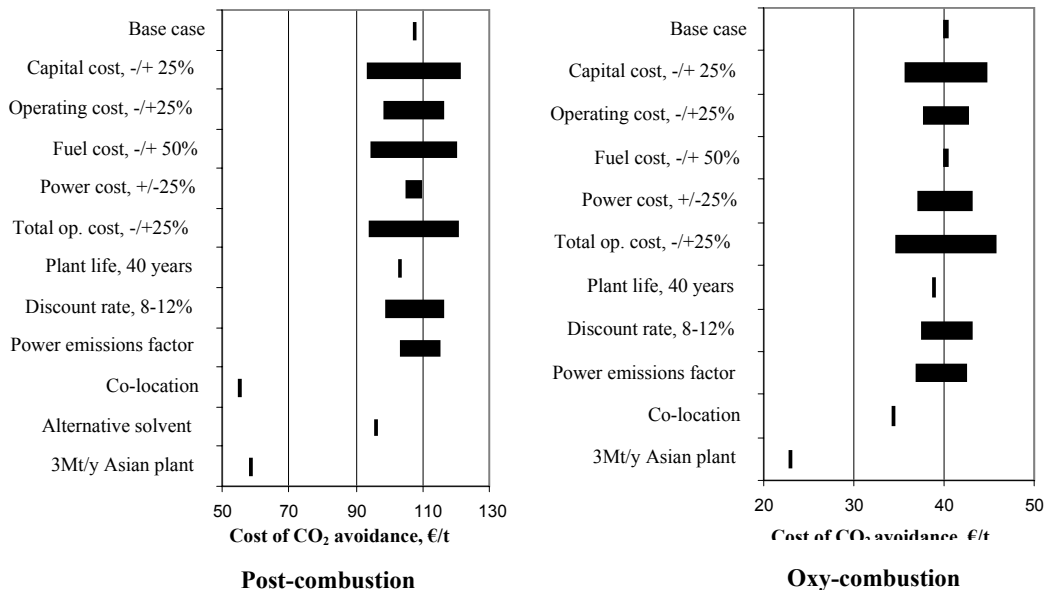Sensitivities to technical and economic parameters are shown in Figure 4.

Figure 4 Post-Combustion and Oxy-Combustion Cost Sensitivities

The emissions associated with the power import/export affect the quantity of net CO_2 emissions avoided. For the base case it was assumed that the emissions were the average of electricity generated in the UK (0.52 kg CO_2/kWh). The sensitivity cases are based on emissions from a new coal fired power plant without CO_2 capture (0.745 kg CO_2/kWh) and a coal fired plant with 85% CO_2 capture (0.14 kg CO_2/kWh).

Some alternative proprietary amine solvents have lower energy consumptions than the MEA solvent used as the basis for this study. The sensitivity to a 25% reduction in steam consumption is shown in Figure 4. Another way of reducing the net cost of steam for post-combustion capture would be to obtain it from an adjacent power plant. If in addition a raw meal with a low sulphur content was used in the cement plant it may be possible to avoid the need for an FGD plant entirely because the sulphur compounds in cement plant flue gas originate mainly from decomposition of minerals during drying and preheating. A sensitivity case involving supply of steam at a cost of €10/tonne and use of a low sulphur raw meal was assessed. The cost of CO_2 avoidance is reduced by almost half to €55/t.

Oxy-combustion cement plants could benefit from co-location with an oxy-combustion or IGCC power plant, because there would be economies of scale in larger oxygen and CO_2 compression and purification plants. The reduction in the cost of CO_2 avoidance is estimated to be approximately €6/t at an assumed oxygen cost of €30/t.

Substantially larger cement plants are being built and operated in some developing countries, particularly in Asia. The cost of CO_2 capture at a 3Mt/y cement plant in Asia was estimated to be significantly lower because of economies of scale and the lower costs of plant construction and operation in developing countries. The estimated cost of CO_2 avoidance by oxy-combustion is €23/t and the cost of post combustion capture is €59/t.

6. Conclusions

Oxy-combustion offers the lowest cost solution for CO_2 capture at new-build cement plants but research and development is needed to address a number of technical issues to enable this technique to be deployed. Costs are estimated to be €40/tonne of CO_2 avoided for a 1 Mt/y European cement plant and €23/t for a 3Mt/y plant in Asia. The estimated costs of post-combustion capture are substantially higher: €107/tonne CO_2 for a 1 Mt/y European cement and €59/t for a 3Mt/y Asian plant. Use of alternative solvents and integration with an adjacent power plant could more than halve the costs. The cost of CO_2 capture at a cement plant using oxy-combustion is expected to be similar to the cost at a typical coal-fired power plant. The quantity of oxygen required per tonne of CO_2 captured is about three times lower at a cement plant but the economies of scale are less favourable. The cost of post-combustion capture at a cement plant is expected to be substantially higher than at a power plant, mainly because of lower economies of scale and the need to install FGD, NO_x reduction and steam generating plant.

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