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Carbon capture in the cement industry: technologies, progress and retrofitting

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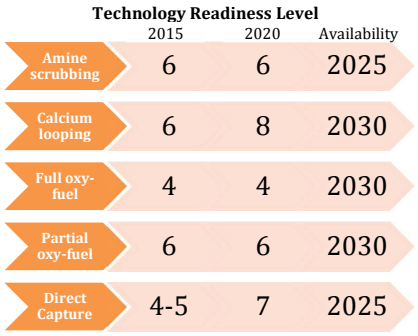

Abstract

Several different carbon capture technologies have been proposed for use in the cement industry. This paper reviews their attributes, the progress that has been made towards their commercialisation and the major challenges facing their retrofitting to existing cement plants. A Technology Readiness Level (TRL) scale for carbon capture in the cement industry is developed. For application at cement plants, partial oxy-fuel combustion, amine scrubbing and calcium looping are the most developed (TRL 6 = pilot system demonstrated in relevant environment), followed by direct capture (4 – 5 = component/system validation at lab-scale in relevant environment) and full oxy-fuel combustion (4 = component/system validation at lab-scale

in lab environment). Our review suggests that advancing to TRL 7 (demonstration in plant environment) seems to be a challenge for the industry, representing a major step up from TRL 6.

The important attributes that a cement plant must have in order to be 'carbon capture ready' for each capture technology selection is evaluated. Common requirements are space around the preheater/precalciner section, access to CO_2 transport infrastructure and a retrofittable preheater tower. Evidence from the electricity generation sector suggests that carbon capture readiness is not always cost-effective. The similar durations of cement plant renovation and capture plant construction suggests that synchronising these two actions may save considerable time and money.

Introduction

Unlike most industrial processes, almost two-thirds (64%) of the CO_2 emissions emanating from the Portland cement industry come from process chemistry rather than from fuel combustion[1]. As shown in Figure 1, around 880 kg CO_2 is generated per tonne of clinker in a typical (1 Mtpa, 3 000 tpd) cement plant[2], which produces CEM I (95% clinker).

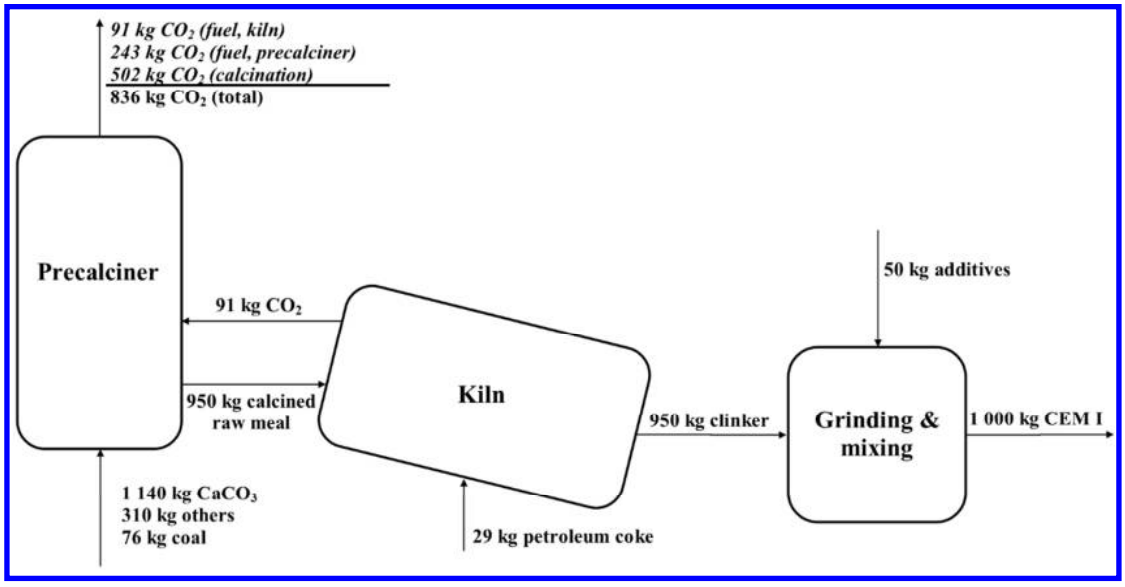

Figure 1: Direct emissions of CO_2 from CEM I (95% clinker) cement manufacture (own calculations). CEM I rather than CEM II was chosen for comparisons in this paper because of its smaller range of composition than CEM II (95 – 100% clinker by weight versus 35 – 94%).

The cement industry is likely to play a role in reducing greenhouse gas emissions to combat anthropogenic climate change. Many decarbonisation pathways suggest that direct specific emission levels of around 350 – 410 kg CO_2/t cement will be required[1,3]. However, increasing clinker substitution, alternative fuel use and thermal energy efficiency[1] can only lead to specific emissions per tonne of cement falling from 730 kg CO_2/t cement in 2009 to about 540 – 590 kg CO_2/t cement in 2050. Alternative, lower CO_2-intensity cements have been suggested but uptake is not expected to be anywhere near the levels required if the sector is to meet these targets[4]. Many NGO-based analysts, such as the IPCC and IEA, agree that the main technology group able to achieve the remaining required emission reductions is carbon capture and storage (CCS)[1,5], owing to the relatively high concentration of CO_2 in the flue gas from these large, point-source emitters[6]. Estimates suggest that the Spanish cement industry could reduce its specific direct emissions by only 21% between 2010 and 2050 without CCS[7], and that UK cement sector absolute CO_2 emissions could be reduced by 66% in the 1990 to 2050 period if CCS is not available but by 81% if it is[8].

However, none of the 45 large-scale CCS projects in design, construction or operation involves the cement industry[9]. Most operating carbon capture plants are in natural gas processing[9], but by 2050 seven industrial sectors could account for about half of CO_2 emissions avoided by CCS[10]. Commercial-scale application of the technology in the cement industry is seen by most as being five to ten years away at best and that few, if any, carbon capture plants will exist before 2030[11–17]. Little research into the practicalities of installing the capture plant at a cement plant, particularly in the case of retrofitting, has been published[18–20]. A lack of effective policy drivers – such as a substantial carbon price, effective strategies to address carbon leakage and promotion of access to capital – is limiting progress and impeding commercial-scale demonstration[11,19,21]. An estimate that failure to develop CCS for industrial applications could increase climate policy costs globally by 221 bn $€_{2013}$/y by 2050[13] illustrates the importance of the technology to the cement sector and other energy-intensive sectors.

This paper starts by developing a new Technology Readiness Level (TRL) methodology for carbon capture at cement plants. The paper then describes the five following promising carbon capture processes: amine scrubbing, calcium looping, full oxy-fuel combustion, partial oxy-fuel combustion and direct capture, before assessing them according to several criteria including the TRL methodology. Based on current R&D efforts, the TRL of each capture technology in 2020 and a date for commercial availability is predicted. Finally, some

of the changes to a cement plant required to enable construction and operation of each carbon capture technology are identified and compared; the most important issues to take into consideration when designing a cement plant which is likely to require retrofitting with CCS in the future are highlighted. It should be noted that this paper focusses on carbon capture technologies, not the complete chain of capture, transport and storage.

Evaluation of carbon capture technologies for cement plants

Technology Readiness Levels (TRLs)

TRLs are used for determining how close to operational deployment a technology is and this approach has been extensively used across CCS literature related to electricity generation[22,23]. In Table 1, we modified electricity generation-specific methodologies from the US Department of Energy Clean Coal Research Program[23] and the GCCSI[22] to be relevant to cement manufacture. The original US DoE TRL specification included two quantitative measures for many of the levels: the size of the process as a percentage of final size of the power station, and a volumetric flow rate of flue gas. This concept has been retained. The flue gas and production rates at each level are equivalent. 'Commercial-scale' is assumed to be a minimum of 1 000 tpd (tonnes of clinker per day), and a demonstration cement plant is assumed to have a capacity at least 250 tpd.

Promising technologies for carbon capture at cement plants

Five promising carbon capture technologies for use at cement plants are described and discussed below. A summary, including costs, is presented in Table 2. For comparison, global average thermal energy consumption in 2012 was 3 530 MJ/t clinker, down from 3 750 MJ/t clinker in 2000[2]. Average electrical consumption was 74 kWh_e/t clinker and 99 kWh_e/t cement in 2012[2]. Typical investment costs for a cement plant in Europe are 250 $€_{2013}$/(tpa)[20]. A 3 000 tpd (1 Mtpa) cement plant produces approximately as much CO_2 as a 125 MW_e coal-fired power station.

Amine scrubbing

This is an end-of-pipe technology; it only involves the flue gas and so does not directly affect the cement manufacture process except, for example, energy management strategies and start up and shut down procedures. Capture rates are expected to be ≥ 90%[24] but some studies have examined lower rates[18].

The thermal energy demand of amine scrubbing is very high (at least 2 GJ/t CO_2)[24] and it generally has to be provided via CHP and/or waste heat recovery. Owing to the paucity of low-grade heat at most cement plants, it may be significantly cheaper to capture only a proportion (up to 50%) of the CO_2 from the plants and not invest in extra heat generation capacity[25]. Furthermore, the flue gas clean-up required increases plant footprint and capital and operating costs[26]. As with all capture technologies, there are knock-on environmental effects from using amine scrubbing[27].

With respect to electricity generation, the technology is at TRL 8 – 9[21]. For cement production, the pilot plant in Brevik, Norway is the most developed, and with a flue gas flow rate of approximately 125 L/s its TRL is 5 – 6[28]. We are not aware of any plans for larger-scale pilot projects in the short- to medium-term. A preliminary estimate of commercial availability is 2025 – 2030, significantly later than the IEA's estimate of 2020[1].

Full oxy-fuel combustion

Oxy-fuel uses a mixture of oxygen (separated from air) and recycled CO_2 as the combustion gas, reducing the CO_2 separation plant's complexity and size[20]. The capture rate is expected to be > 90%[29].

Although energy efficiency[30] and clinker throughput[31] are expected to improve in an oxy-fuel cement plant, an air separation unit (ASU) using up to 60 kWh_e/t clinker is required to produce pure oxygen for the process[29]. Alternative processes for oxygen production are being developed which could reduce the energy penalty[24].

Unlike the other four technologies, full oxy-fuel combustion will affect the whole cement plant. The design of virtually every unit is different from a traditional cement plant to take account of different gas properties and to minimise gas ingress or egress from the units[20]. This is likely to be technically achievable but expensive; on this basis we agree with others[19] that retrofitting full oxy-fuel capture to an existing cement plant is unlikely to be an attractive proposition. New-build full oxy-fuel cement plants are expected to cost around 220 – 290 $€_{2013}$/t annual clinker capacity (€/(tpa))[8,32,33]. Applying a 50-year lifetime and a 10% discount rate, this capital cost alone is equivalent to 22.2 – 29.2 €/t cement. Similar numbers calculated for the other technologies are given in parentheses after their capital costs.

Full oxy-fuel is seen by some[20] as the best technology for new-build low-carbon cement manufacture, but development is difficult because the next stage is the construction of a whole, albeit small, cement plant. Its

TRL is 4 and until the ECRA's €50M, 500 tpd pilot plant is funded[34] this is not expected to increase; however, such progress could raise full oxy-fuel's TRL to 8. This step seems to be without the remit of most research organisations (such as universities) and to the authors' knowledge no company has announced any intention to fund such a pilot plant in the near- or medium-term. An estimate of commercial availability is 2030 – 2040.

Partial oxy-fuel combustion

The difficulties with applying full oxy-fuel combustion have led to a 'partial oxy-fuel' approach where the preheaters and precalciner are oxy-fuelled and the kiln and cooler are air-fuelled (i.e. conventional). It is expected that the capture rate could be as high as 70%[20,35]. The preheaters and precalciner would have to be redesigned and made gas-tight, but retrofitting is expected to be easier than for full oxy-fuel because the kiln and cooler would not change. Since 75% of the fuel is burned in the precalciner it is assumed that a partial oxy-fuel ASU would require about 45 kWh_e/t clinker[20]. A partial oxy-fuel retrofit is expected to cost around 85 €/(tpa)[32] (8.6 €/t) whilst new-builds are expected to be in the region of 225 – 275 €/(tpa)[20,35] (22.7 – 27.7 €/t).

A 30 – 50 tpd pilot plant has been built by a consortium including Air Liquide, FLSmidth and Lafarge, and a feasibility and cost exercise regarding retrofitting partial oxy-fuel to a cement plant undertaken[36]. Its TRL is therefore 6, but without the next step of a full FEED study it is unlikely to increase soon[37]. A preliminary estimate of commercial availability is 2025 – 2035, similar to the IEA's estimate of 2025[1].

Calcium Looping (CaL)

Calcium looping (CaL) involves chemical reactions between CO_2 and calcium oxide sorbent in a pair of circulating fluidised beds. There are energetic and waste benefits that can be achieved by integrating CaL with cement manufacture from using $CaCO_3$ as a sorbent precursor and operating at > 600°C[38]. High-grade 'waste heat' from the process can be used to generate additional electricity; this should be about the same as the amount required by the cement, capture and CO_2 compression plants combined.

An ASU using about 20 kWh_e/t clinker would be required to produce oxygen for the calciner. Fuel consumption would increase by about 50% but the CO_2 avoidance rate is expected to be ≥ 90%[35]. The preheaters would need altering to take into account the diversion of limestone from the usual raw meal entry point at the first preheater to the CaL calciner; Ozcan et al.[39] assume that the waste CaO sorbent would be

mixed with the rest of the raw meal between the precalciner and kiln (the 'diversion' design). The flue gases would flow into the CaL carbonator between the third and second preheaters. Alternatively, the CaL calciner could replace the precalciner (the 'replacement' design)[35]. Another rather different design ('HECLOT', by ITRI) uses a rotary kiln calciner; this could encounter the same issues surrounding gas-tightness as full oxy-fuel combustion[40,41].

The largest project so far is HECLOT in Taiwan, which captures 1 tCO_2/h from 3.1 t/h flue gas using the rotary kiln calciner[40]. Thus, CaL in the cement industry is at TRL 6. ITRI is planning to build a larger plant in 2017 which, if successful, will raise the TRL to 8[40]. There are no known plans to build a cement-based CaL pilot plant with a fluidised bed calciner. A preliminary estimate of commercial availability is 2025 – 2030.

Direct Capture

Direct capture only captures emissions coming from the calcination of limestone, which account for about 64% of the CO_2 generated at a typical cement plant[1]. This process is being developed by Calix, an Australian company. Most of the information in this section comes from the company directly, via the website and from discussions with employees[42].

Direct capture occurs in a vertical shell-and-tube heat exchanger known as a direct capture unit (DCU). Raw meal and steam pass down the tubes and are heated and calcined by heat transferred from flue gases from a combustion process flowing through the shell. Because no external gases enter the tubes, the gas coming out of them is a virtually pure CO_2/steam mix. After steam knock-out, the CO_2 should be suitable for compression[42].

The DCU will replace the precalciner and receive hot raw meal from the preheaters. Modelling by Calix suggests that the energy penalty after heat integration will be ± 2% of the thermal energy requirement of the cement plant[43]. Retrofitting should be relatively easy because it requires the replacement of only the preheaters and precalciner.

A pilot plant has operated with an equivalent capacity of 160 tpd clinker. The lack of information about the impurities in the raw meal limits its TRL to 4. Calix is planning to build a 320 tpd pilot plant at a European

cement plant before 2020 and successful operation will raise the TRL to 7. A preliminary estimate of commercial availability is 2025 – 2030.

Prospects for further development and technology champions

If there were great pressure to commercialise cement CCS as soon as possible, amine scrubbing would likely be the first available, but the lack of such pressure offers other technologies the chance to catch up. Amine scrubbing's main problem is its cost (see Table 2); a cheaper alternative at a similar level of development would stand a good chance of supplanting it. However, no technology is likely to be widely available before 2025.

Direct Capture and Calcium Looping seem to be progressing fastest and possibly could reach TRL 7 by 2020; no other technology is expected to reach this level soon although partial oxy-fuel combustion could overtake them if the AL/Lafarge/FLS consortium decides to progress with trials.

Scale-up can require significant investment; the six-tenths 'rule'[45] suggests that increasing the scale of a process by an order of magnitude will quadruple capital investment costs. Building the confidence of potential investors or developers is critical for carbon capture projects because most of the technologies are developed by a sequence of organisations on the path to commercialisation.

In this context, TRL 7 seems to be the major obstacle for capture processes in the cement industry. This may be because it is the point at which traditional university-led research is too small-scale to develop the technology further. Companies or larger research institutions acting as a 'champion' for a specific technology are generally more suited to carry on development beyond TRL 6. Such organisations are Calix (direct capture) and ITRI (calcium looping). The ECRA, as a research collaboration of several cement manufacturers, does not necessarily have the independence and resources to develop a pilot-scale oxy-fuel plant. Although the AL/Lafarge/FLS consortium (partial oxy-fuel) would appear to have massive financial and technological resources, it is likely that limited funds and scope prevent it from continuing development. Amine scrubbing has many champions but whether much of their focus is on the cement industry is debatable. The absence of commercial reasons to invest in a decade-long development & demonstration programme makes TRL 7 virtually impossible for technologies currently championed by universities and small research institutes.

Of particular interest to plant owners may be technologies that can be installed, if not operated, at a low extra cost. Designing a process to be easily convertible to partial oxy-fuel (e.g. more air-tight preheaters) may help to reduce costs in the long-run; this is discussed below. Furthermore, direct capture theoretically offers 50 – 60% capture for very little added cost for new-builds. It is possible that such a plant could be built and run competitively until the rest of the CCS chain is available.

Technologies such as amine scrubbing, which are already in use in other industries, have the benefit of learning within those industries as well as design and equipment suppliers with relevant experience. Oxy-fuel systems should not suffer too much in this respect; oxygen production is similar across industries and although changes to all major process units are required, these should be well within the competencies of cement plant manufacturers. Direct capture and CaL are quite process-specific so are unlikely to benefit in this respect.

Early indications are that retrofitting a cement plant with some form of carbon capture (except amine scrubbing) will have a capital cost in the region of 100 €/(tpa) (10.1 €/t) compared with a reference new-build cement plant cost of approximately 250 €/(tpa)[46] (25.2 €/t). A new-build cement plant with carbon capture is expected to cost in the region of 300 €/(tpa) (30.3 €/t). Costs of CO_2 avoided are around 20 – 80 €/t CO_2, again excepting amine scrubbing. It is more difficult to gain a clear picture here because of the different discount rates used across the literature which range from 6% to 16% but tend to cluster around the 8 – 10% region[23,24,35,47].

The range of capital costs for amine scrubbing varies wildly, and this is in part due to assumptions about the source of the extra energy for stripping the CO_2 from the solvent[18,32]. Most studies focus on MEA solvent[18,20,30,48]; it is more likely that more advanced amines would be used, reducing both the capital and operating costs.

Any capture process must allow the cement plant to continue to produce in-spec cement. Amine scrubbing should not have a significant effect beyond affecting the energy management on site unless waste heat recovery is installed on the kiln. Cycling calcium oxide (or all the raw meal) through a calcium looping system will affect the physical properties of the solids, something which could have an effect on cement quality and is currently being studied batch-wise in laboratories. Direct capture's DCU could also have an effect on the properties of the calcined raw meal, and the pilot plant planned for construction by 2017 should

produce relevant data to evaluate possible effects. In-spec cement was created during full oxy-fuel laboratory studies. It can be expected that by 2020 the quality of cement made in a plant with any of these capture process attached will have been tested and hopefully confirmed to be within relevant standards such as EN 197[49].

Retrofitting cement plants with carbon capture technology

At some point it may be necessary to attach carbon capture facilities to an existing cement plant, a process known as retrofitting. The IEA assumes that the retrofitting of existing point-source emitters with carbon capture is likely to be necessary from 2020 in order to reach emission targets[3]. Retrofitting is generally seen to be more difficult and expensive than applying CCS to new-builds because there may be issues surrounding access, plant footprint and management of fuels and other resources. The plant must also be shut down for the installation of the new equipment. Only a few sources in the literature have discussed these issues[32]. A contribution to this topic is provided below.

Shutdown time

Fixed costs represent approximately 40% of total costs of operation[50] so closing down a plant for an extended period leads to significant financial repercussions. Any overruns in construction and commissioning would add yet more costs, with fixed costs alone being in the order of €3M per month for a typical 1 Mtpa clinker plant[51].

The first significant retrofit of a power station with CCS was of Boundary Dam Unit 3 with amine scrubbing, which started operation in October 2014. Putting aside the testing and commissioning time, the construction took thirteen months although it should be noted that the power station unit was refurbished at the same time[52].

Cement plants undergo various shutdowns for repairs, maintenance and improvement. These range from short annual shutdowns of around a month to longer shutdowns performed maybe once in a generation; modernisation of complete plants can take more than a year. This can be compared with the construction of a new cement plant, which takes around 18 – 24 months. (These durations come from promotional material, so cannot be assumed to be representative of the industry as a whole[53].)

Thus, the time periods for refurbishment of cement plants and installation of carbon capture at power stations are similar. This suggests that applying carbon capture during a cement plant refurbishment may be the most convenient strategy, in a manner similar to Boundary Dam Unit 3. Changes to virtually all process units will mean the shutdown period for full oxy-fuel combustion is likely to be long. By contrast, connecting a pre-constructed amine scrubbing plant to the preheater exhaust may be possible within the period of an annual shutdown (about a month). The other technologies will likely fall somewhere in between.

Carbon Capture Readiness (CCR)

The length (and cost) of shutdown periods for installation of the different technologies may ultimately become a major determinant of which of them, if any, are competitive. A way to reduce this time and expense could be by designing the cement plant to be 'carbon capture ready' from the outset. Although CCS is not currently viable in the cement sector, plant owners may wish to ensure that they can install it with minimal disturbance once it is. Alterations to the original design of the site and the cement plant itself to make them CCR could reduce time and cost during retrofitting for a small up-front investment.

Published work on CCR in the cement sector has focussed on amine scrubbing. Liang & Li[18] provide a list of 21 criteria split into six categories for assessing the potential to retrofit cement plants with amine scrubbing: extra space on site, access to storage capacity, water supply, sufficient electricity & steam, cement production technology and flue gas properties. The IEA GHG[30] states that the four main requirements for amine scrubbing retrofitting are land, electricity import, steam production and removal of certain gases from the flue gas. The first is simple to understand – the new units require space – but this may not be so easy in practice, as cement plants are often surrounded by land which is unsuitable or that belongs to another entity. Electricity can either be imported from the grid or produced on site, but again this will require space and/or money. Amine scrubbing requires low concentrations of NO_2, SO_2 and O_2 in the flue gas so a pre-treatment stage will be necessary; this is not an insurmountable challenge.

To better understand the requirements of each technology for CCR, the changes to each relevant unit in the cement manufacturing process are compared in Table 3. Some site-wide considerations, and those concerning new units, have also been identified. The preheaters usually need to be replaced because they will have to handle a gas mix with different properties (full oxy-fuel) and/or a different mass flow rate (CaL, direct capture

& partial oxy-fuel). Oxy-fuel systems also require more air-tight units. Attaching amine scrubbing could change the operating conditions of the preheaters because a large enough pressure gradient will be required to ensure the gases flow from the preheaters to the capture plant. Preheaters at a 'diversion' design CaL plant will require tie-in locations where the gases can be diverted to the capture plant and back again.

The precalciner will require changes in all cases except amine scrubbing and 'diversion' calcium looping; in a 'replacement' design it will be replaced by the CaL calciner. In direct capture the precalciner will be replaced with the direct capture unit (DCU) which will require a larger area and a new raw meal conveyance system between the preheaters and DCU may be required. In oxy-fuel combustion, the design of the precalciner will need to change slightly to take into account the altered gas and flame properties but it should be possible to fit it in roughly the same area as an air-fuel precalciner.

The kiln and coolers will only require alterations in full oxy-fuel, and in this case full replacement is likely to be the most practical option, with new, air-tight designs being installed. A two-stage cooler will be required, in which the first stage uses recycled CO_2 and the second stage air to cool the clinker[20].

Since none of the carbon capture technologies is yet available, cement plant owners may not wish to invest in CCR based on one technology. However, there are several common requirements across all or most of the technologies. By identifying these and considering whether they merit investment up front, the plant owner can reduce retrofitting costs without locking himself in to one technology. Some major considerations for each technology are shown in Table 3 and the ones in common are discussed below.

Critical issues for CCR

The availability of land for expansion is already a concern at many sites and may be the factor which prevents or delays roll-out of CCS at some of them. Plant layout is related to this issue; all capture technologies require space at specific locations around the cement plant so ensuring that existing units do not have to be moved a few metres to make room for others could greatly reduce shut-down time. Setting aside space solely to facilitate easier construction and access on-site during retrofitting could also reduce shut-down costs. In all cases, a CO_2 compression and temporary storage facility will require space. In general, relatively large zones should be reserved for the capture plant close to the preheater tower and precalciner/kiln connection.

Cement plants tend to be located on limestone deposits; although some researchers have suggested that plants are built within the region of a CCS cluster[19], it is unlikely that this will happen except where the cluster is located upon a suitable geological formation. Limestone is not suitable for CO_2 storage so there is likely to be a need for significant and reliable CO_2 transport between plant and storage site. Purchasing, or having an option to purchase, the storage capacity is also extremely important[32]. Discussions with local authorities on planning applications for capture plants and CO_2 pipelines at the time of cement plant construction could increase the chance that the plant and pipeline can be built when required. These issues are not unique to the cement sector and so are not discussed in more detail here.

Other important issues for CCR

Some items may be relatively cheap to construct when building the original cement plant, but difficult or expensive to alter later on. For example, if some or all of the major pipe-runs for the capture plant are installed at the same time as those for the cement plant itself, fewer changes are likely to be required later and perhaps a shorter shut-down will be possible. Several of the technologies would benefit from the preheater tower being adaptable to house the new preheaters and/or precalciner. However, care should be taken in choosing to apply CCR without assessment of the benefits. For example, Bohm et al[54] determined that CCR costing 4% of the total cost of the plant made little difference to the economics of IGCC power stations. Lucquiaud et al. suggest that making a pulverised coal power station CCR could cost less than 1% of capital costs[55], and Liang et al. determine that such power stations in China are up to 10% less likely to close early[56]. Rohlfs & Madlener calculated that it was usually more cost-effective to close a modern, unabated power station and replace it with a completely new abated power station[57]. Discounted cash-flow analysis can identify whether the extra capital expenditure for particular items is financially attractive or more extensive rebuilding or replacement at a later date is more suitable. This is not applicable for some particular items such as land – if the plant does not have room to build the capture facilities on existing land or expand into adjacent areas, the capture plant may never be built regardless of the profitability.

In conclusion, carbon capture in the cement is several years away but timely consideration of the challenges which lie ahead, such as retrofitting and ensuring cement plant/capture plant compatibility, will reduce their complexity in the long run. The lack of large-scale (> 50 tpd) pilot plants in the cement industry is currently the biggest impediment to further capture technology development and commercialisation.

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332 **Table 1: Technology Readiness Levels for CCS in the cement industry**

TRL	Definition	Description
1	**Basic principles observed and reported**	Lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples include desktop studies of a technology's basic properties.
2	**Technology concept and/or application formulated**	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies.
3	**Analytical and experimental critical function and/or characteristic proof of concept**	Active R&D is initiated. This includes analytical and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology (e.g., individual technology components have undergone laboratory-scale testing using bottled gases to simulate major flue gas species at a scale of < 0.5 L/s, and simulated raw materials).
4	**Component and/or system validation in a laboratory environment**	A bench-scale prototype has been developed and validated in the laboratory environment. Prototype is defined as < 1 tpd (e.g., complete technology process has undergone bench-scale testing using synthetic flue gas composition at a scale of < 20 L/s, and simulated raw materials).
5	**Laboratory-scale similar-system validation in a relevant environment**	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Prototype is defined as < 1 tpd clinker scale (e.g., complete technology has undergone testing using actual flue gas composition at a scale of < 20 L/s and actual raw materials).
6	**Engineering/pilot-scale prototypical system demonstrated in a relevant environment**	Engineering-scale models or prototypes are tested in a relevant environment. Pilot or process-development-unit scale is defined as 1 – 50 tpd (e.g., complete technology has undergone small pilot-scale testing using actual flue gas composition at a scale equivalent to 0.04 – 1 Nm^3/s and actual raw materials).

7	**System prototype demonstrated in a plant environment**	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Final design is virtually complete. Pilot or process-development-unit demonstration of a 50 – 250 tpd clinker scale (e.g., complete technology has undergone large pilot-scale testing using actual flue gas composition at a scale equivalent to approximately 1 – 4.5 Nm^3/s and actual raw materials).
8	**Actual system completed and qualified through test and demonstration in a plant environment**	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include start-up, testing, and evaluation of the system within a ≥ 250 tpd plant with CCS operation (e.g., complete and fully integrated technology has been initiated at full-scale demonstration including start-up, testing, and evaluation of the system using actual flue gas composition at a scale equivalent to ≥ 4.5 Nm^3 and actual raw materials).
9	**Actual system operated over the full range of expected conditions**	The technology is in its final form and operated under the full range of operating conditions. The scale of this technology is expected to be ≥ 1000 tpd plant with CCS operations (e.g., complete and fully integrated technology has undergone full-scale demonstration testing using actual flue gas composition at a scale equivalent to ≥ 18 Nm^3 and actual raw materials).

333 **Table 2: CO_2 capture from the cement industry: technology comparisons**

Attribute	Amine scrubbing*	Calcium looping	Full oxy-fuel	Partial oxy-fuel	Direct capture
Capital cost (€$_{2013}$)	213 M for 2 Mtpa RF (China)[18] 440 – 540 for 1 Mtpa NB[32] 245 – 350 for 1 Mtpa RF[32]	269 M NB (inc cement plant cost) for 1 Mtpa[35] 125 M NB (capture plant only) for 1 Mtpa[35]	291 M for 1 Mtpa NB[32] 104 M for 1 Mtpa RF[32]	97 – 107 M for 1 Mtpa RF[35] 85 M for 1 Mtpa RF[32] 275 M for 1 Mtpa NB[32]	Unknown.

Overall cost, avoided ($€_{2013}$/t CO_2)	46 – 57 NB @ DR 6 – 16 %[18] 51 NB @ DR 7 %[48] 107 NB @ DR 10 %[58] 52 – 104 @ DR 8 %[32] 143 – 187 RF @ DR 10 %[15] 172 – 333 (short-term) 86 (long-term)[47] 53 RF[18]	75 – 85 RF @ DR 10 %[15] 18 NB[35] 31 NB[59]	39 NB @ DR 8 %[32] 41 RF @ DR 8 %[32]	49 NB @ DR 8 %[32] 54 RF @ DR 8 %[32] 12 NB[35] 54 – 69 RF[37] 58 RF[32] 62 RF[36]	Unknown
Typical capture rate	> 90 %	> 90 %	> 90 %	65 %	60 %
Complexity	Low: mature end-of-pipe technology, but extensive FG clean-up is required before capture	Medium: integration should be simple but fluidised bed combustor operation is outside cement industry knowledge	High: Increased design and maintenance complexity; operation of the plant changes, especially in kiln and cooler. Kiln stop likely if O_2 supply fails.	Medium: Increased design and maintenance complexity (although less than full oxy-fuel); operation of the plant should be relatively similar to unabated cement	Low: Operational knowledge of direct capture in cement industry currently non-existent except for one company but kiln/cooler section identical to before.
Major changes to cement process	None	Precalciner replaced with dual fluidised beds (or, for	New preheaters and precalciner necessary.	New preheaters and precalciner necessary.	Precalciner replaced with direct capture unit (DCU) tower.

		HECLOT, one fluidised bed and a rotary kiln), steam cycle and associated equipment	Changes to kiln burner and cooler designs necessary. False air flow reduction requires altered designs of units		
Capture plant footprint	Large because of installation of SCR & FGD systems as well as capture plant[26]	Possibly slightly larger than partial oxy-fuel but smaller than full oxy-fuel. CO_2 processing unit required to remove chlorides & water. A steam cycle will need to be installed.	Relatively large - air separation, waste heat recovery and CO_2 processing units will take up space.	Medium (0.5 ha) – air separation, waste heat recovery, FG recycling and CO_2 processing units will take up space, but lower capture rate and O_2 demand means they will be smaller than full oxy-fuel	Small. DCU tower likely to be shorter but wider than a preheater tower; gas treatment plant will be small due to low capture rate and inherent purity of CO_2 (only water removal necessary)
Cement quality	No change expected	No change observed at lab scale	No change observed at lab scale	No change observed at lab scale	Unknown
Retrofittability	Easy, since few changes to the cement plant itself are required. Physical connection to cement plant probably possible in annual shutdown	'Diversion' and 'Replacement' designs: Possible, but prolonged shutdown likely while dual FBCs installed. Space may be	Technically possible but doubts about practicality remain. Long shutdown expected for installation of new equipment and	Relatively easy. Precalciner and preheater replacement will require a lengthy shutdown, but length (and risks) not as great as for full oxy-fuel.	Relatively easy. Probably similar to partial oxy-fuel as both require preheater & precalciner replacement. Modular nature of capture technology should enable

	period. Space for capture plant may be an issue on many sites.	a constraint. 'HECLOT': replacement of kiln will cause a long shutdown. As with full oxy-fuel, practicality of gas-tight rotary kilns must be demonstrated	alteration of existing units		some prefabrication and reduce construction times on site
Current Technology Readiness Level (TRL) with respect to cement manufacture	**6** 0.125 Nm^3/s real FG scrubbed[28] (ca. 0.2% of full size)	**6** 3.1 tph FG (0.7 Nm^3/s FG) HECLOT PP in operation in Taiwan[59] but results not yet published (1.2% of full size)	**4** Lab-scale tests undertaken, but no PP built yet[20]	**6** 2 – 3 tph RM (1.3 – 2 tph) pilot plant in Denmark operated successfully[37]	**4-5** One-tube (10 tph RM, 6.6 tph/160 tpd) tests undertaken, but not at a cement plant with only with high-purity RM. Heat integration not tested[43].
TRL expected in 2020 assuming successful completion of current plans	**6** No new amine scrubbing PP projects in cement sector are currently known	**8** ITRI plans to build a 30 MW_t (11 Nm^3/s, 20% of full size) HECLOT PP in 2017[59]	**4** ECRA plans to build a 2 tph PP seem to be on hold so unlikely to be completed by 2020	**6** Consortium not progressing with FEED because of lack of viable business model[37]	**7** 20 tph RM (ca. 13 tph/320 tpd clinker, 10 % of full size) PP to be built in 2018 – 2020.
Time until wide availability	10 – 15 years	10 – 15 years	15 – 25 years	10 – 20 years	10 – 15 years

334

335 **RF** = retrofit. Includes only cost of capture plant. **NB** = New-build. Includes cost of cement plant (usually about 150 M€ in Europe). **DR** = discount rate. **RM** = raw meal. **FG**

336 = flue gas. **PP** = pilot plant. **Full size** = 3 000 tpd clinker (1 Mtpa), or 55 Nm^3/s flue gas. *Includes the cost of CHP for heat provision.

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339 **Table 3: Technology-specific considerations for designing capture-ready cement plants**

<table>
<tr><th>Aspect of plant</th><th>Amine scrubbing</th><th>Calcium looping</th><th>Direct capture</th><th colspan="2">Oxy-fuel</th></tr>
<tr><th></th><th></th><th></th><th></th><th>Partial</th><th>Full</th></tr>
<tr><td>Raw materials & fuel handling; utility connections</td><td>If a CHP plant is to be built, the fuel supply should be considered. This may include a natural gas pipeline connection.</td><td>More fuel (ca. 50%) will be required on site so storage & handling facilities could be designed to accommodate this from the start. Combustion of alternative fuels in a CFB may be difficult so coal facilities may be the most important to over-size.</td><td rowspan="2">If necessary, a source of purer (i.e. low-Cl) raw materials should be identified</td><td colspan="2" rowspan="2">A larger electricity grid connection should be installed so that enough electricity can be imported to run the ASU and other capture equipment</td></tr>
<tr><td colspan="2">Cooling and process water connections will be necessary</td></tr>
<tr><td rowspan="3">Preheaters</td><td colspan="5">The ability to connect the flue gas exhaust to the gas clean-up system should be included.</td></tr>
<tr><td rowspan="2">The exhaust from the preheaters will go to the FGD plant. Enough pressure will have to be present to let it flow; this may affect plant</td><td colspan="4">The tower should be built to a specification whereby it can accommodate the new design of preheaters required in the capture plant.</td></tr>
<tr><td>Tie-in locations for connection to the CaL calciner should be designed and included (‘diversion’ design)</td><td>The preheaters should be at a height to allow good</td><td colspan="2"></td></tr>
</table>

	design or require the installation of an extra fan		connection between them, the DC calciner and the kiln.		
Precalciner	No action necessary.	The connections between the calciner and the kiln and preheaters should be appropriate for re-connection to the CaL calciner (‘replacement’ and ‘HECLOT’ designs)	Sufficient space for the larger direct capture calciner is necessary.	The calciner housing design must be able to accommodate the post-retrofit calciner.	
Kiln	No action necessary.				The kiln should be as airtight as possible. The region around the burner, including the air supply should be suitable for retrofitting with the new burner and gas supply. The kiln must be compatible with the refractory required for oxy-fuel combustion
Cooler	No action necessary.				The cooler, or at least the site of the cooler, should be adaptable

					for oxy-fuel operation. This may include building a two-stage cooler, which is likely to be larger than a standard cooler.
Plant footprint	A very large amount of land will be required to build the capture facilities. This should be close to the preheater exhaust. The CHP plant should be built close by to reduce the distance that the steam has to be transported	The cement plant may require a different layout to ensure that a CaL system can be fitted between the preheaters and kiln or within the preheater train. Space for the ASU and steam cycle should be provided relatively close to the CaL plant location, and gas clean-up and compression should not be too far away from the calciner.	A small amount of land will be required to accommodate the DCU and flash condenser.	A significant amount of land will be required for an ASU and the recirculation loop. Land for the gas clean-up plant should be made available close to the preheater tower.	
Other	Gypsum will be produced on-site from the FGD plant; disposal or sale of this should be considered			Purification & compression plant for partial oxy-fuel plant (1 Mtpa) would require 0.5 ha.	

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TOC
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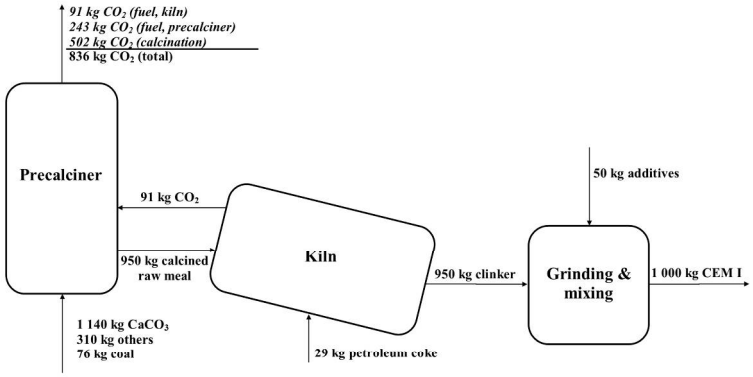

Figure 1: Direct emissions of CO2 from CEM I (95% clinker) cement manufacture (own calculations). CEM I rather than CEM II was chosen for comparisons in this paper because of its smaller range of composition than CEM II (95 – 100% clinker by weight versus 35 – 94%).
209x147mm (300 x 300 DPI)