A paper prepared by the IEA in collaboration with CCUS Action Group members with expert contributions from the Working Group on CCS in Industrial Applications as a contribution to the 4th Clean Energy Ministerial 2013. It is not a publication of the IEA and as such its conclusions do not constitute a position of the IEA.

CCUS AG Working Group on CCS in Industrial Applications Background Paper

The transition of energy-intensive industrial sectors to a low carbon economy, while maintaining their competitiveness, requires concerted, collaborative efforts. These will be required to develop and invest in novel process designs and solutions that can reduce emissions intensities by over 50%, but for which there is not yet a market. In this context, it appears that carbon capture and storage (CCS) will become an indispensable tool, but it has been given insufficient attention to date by most sectors and governments. The CCUS Action Group's Industrial CCS Working Group aims to identify opportunities and policies to advance CCS in industrial applications in the near-term.

1. Introduction

This background paper briefly describes the state of knowledge on the current and future application of CCS to industrial applications. It provides a foundation for the Industrial CCS Working Group of the CCUS Action Group – initiated at the 3rd annual Clean Energy Ministerial (CEM3) in London – to develop its work on the task of spurring action in the area of supporting CCS in industry. The objectives of this Working Group, as set out in the work plan document, are:

1. To raise awareness among CEM governments of the potential of CCS for significantly reducing emissions in industrial applications, including an improved level of differentiation between the sectors and processes concerned.
2. To analyse, on the basis of existing studies and expert input, the potential and challenges for CCS in the industrial applications that offer the greatest opportunities for: reducing overall CO_2 emissions (i.e. long-term large contributors of CO_2 emissions); and/or near-term CO_2 emissions reduction (i.e. low cost opportunities for application of CCS).
3. To provide CEM governments with a succinct set of near-term actions required to advance industrial CCS towards deployment consistent with lowest-cost climate change mitigation and industrial competitiveness.

The Working Group is led by the IEA and the UK Carbon Capture and Storage Association (CCSA) on behalf of the CCUS Action Group members. The next step is to undertake further analysis on the issues laid out in this paper though a mixture of stakeholder interviews, workshops and desktop research. The findings will be incorporated into a final briefing paper to be presented to CEM4 in New Delhi in April 2013.

"CCS in industrial applications" refers to the capture, transport, (utilisation) and storage of CO_2 that would otherwise have been emitted from commercial facilities excluding the power sector[1]. CCS in this paper refers to the use of geological storage to permanently isolate CO_2 from the atmosphere. It is possible that the captured CO_2 could also be utilised in industrial applications, possibly before being stored. However, this paper focuses primarily on the capture of CO_2 and generally assumes that this CO_2 will be transported to geological storage sites for climate change mitigation purposes, or that any industrial uses of CO_2 will lead to the captured CO_2 being isolated from the atmosphere in the very long-term.

2. Rationale

In its consideration of cost-effective scenarios for the stabilisation of greenhouse gas levels in the atmosphere at levels consistent with a maximum two degree rise in global temperature, the IEA finds that CCS should be applied to a number of sectors that currently emit very significant quantities of CO_2 from large stationary point sources, as well as those sectors that stand to increase their CO_2 emissions in coming decades[2] (IEA, 2012). One of these sectors, the power sector, is closely associated with CCS. Innumerable publications, conferences, policy documents and R&D investments reflect the ongoing efforts worldwide to deliver a power generation fleet that enables fossil fuel use without compromising climate change mitigation. The other seven industrial sectors combined, according to IEA analysis, are equally as important in terms of the CO_2 that they would capture and store by 2050. The breakdown of stored CO_2 in 2050 is shown in Figure 1.

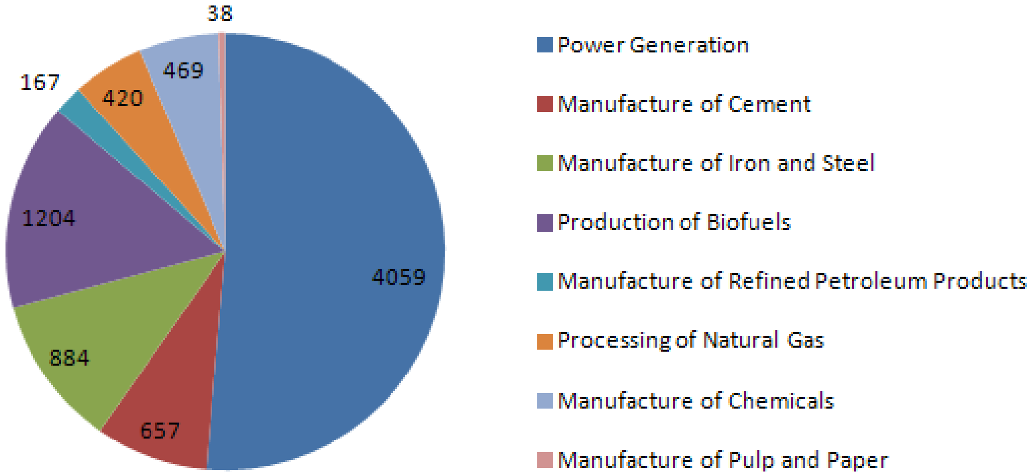

Figure 1. $MtCO_2$ stored annually from different sectors in 2050 in the 2DS scenario[3] (IEA ETP 2012 figures)[4]

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[1] Where power is generated and predominantly consumed on the industrial site rather than exported, this is included. For example CHP plants on a refinery site.

[2] For example, liquid fuels production from biomass.

[3] The 2DS (2 degree scenario) scenario is one scenario modelled for meeting the goal of limiting global temperature rise to 2˚C.

As Figure 1 shows, it is not possible to categorise CCS in industrial applications as a single subdivision of CCS, alongside CCS in power generation. In fact, as is described in this paper, applying CCS to industrial applications requires consideration of a variety of different CO_2 sources and technology options within each sector. In comparison to the power sector, the challenges facing CCS in industrial applications – in terms of policy, economics and technology – have not received widespread attention and, as such, there is a low awareness of what actions should be taken to enable all of the sectors in Figure 1 to make use of CCS in order to meet agreed climate goals. However, from the perspective of achieving the lowest cost emissions reductions in the global economy, CCS in certain industrial applications presents significant potential for *lower* cost CO_2 cuts, sometimes at larger scales than the power sector.

Failure to make the case for CCS in industrial applications and the associated necessary actions poses a significant threat to the world's capacity to tackle climate change. In some sectors, such as the manufacture of cement and iron and steel, CCS is currently the only large-scale mitigation option available to reduce emissions rates below 50% of their current levels. Without CCS it may not be possible to decarbonise these sectors and therefore economies with a large proportion of heavy industries that they wish to retain could find that their decarbonisation efforts have an inconvenient limitation. The reason for this is that certain industrial processes unavoidably generate CO_2 as a result of chemical reactions that are integral to the formation of the final product. These emissions are known as 'process' emissions and it is important to distinguish these from 'combustion' emissions. Process emissions are released by non-combustion chemical processes. Activities that have high levels of process emissions include:

- Lime calcination (Manufacture of Cement)
    - $CaCO_3 \rightarrow CaO + \mathbf{CO_2}$
- Iron ore reduction with coke or natural gas (Manufacture of Iron and Steel)
    - $Fe_2O_3 + CO + 2C \rightarrow 2Fe + 2CO + \mathbf{CO_2}$
    - $4Fe_2O_3 + 3CH_4 \rightarrow 8Fe + 6H_2O + 3\mathbf{CO_2}$
- Ethylene oxide production by direct oxidation (Manufacture of Chemicals)
    - $7C_2H_4 + 6O_2 \rightarrow 6C_2H_4O + 2H_2O + 2\mathbf{CO_2}$
- Aluminium electrolysis (Manufacture of Non-Ferrous Metals)
    - $2Al_20_3 + 3C \rightarrow 4Al + 3\mathbf{CO_2}$
- Hydrogen or synthesis gas production (Manufacture of Chemicals / Manufacture of Refined Petroleum Products)
    - $CH_4 + 2H_2O \rightarrow 4H_2 + \mathbf{CO_2}$
    - $C + H_2O \rightarrow CO + H_2$ / $CO + H_2O \leftrightarrow H_2 + \mathbf{CO_2}$
- Fermentation (Production of Biofuels/Manufacture of Food Products and Beverages)
    - $C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2\mathbf{CO_2}$

Where a carbon-containing fuel is burned, or where the main purpose of the oxidation of the fuel is to use the heat released, the resulting emissions are considered to be combustion emissions. Combustion emissions in most industrial applications could be reduced through exploitation of energy efficiency improvements and could also be partly mitigated by employing non-fossil energy to provide heat or power. However, many industries, such as oil

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[4] Hydrogen production ($2MtCO_2$/yr) is allocated to the Manufacture of Chemicals, except hydrogen specified as part of refineries.

refining, have developed very integrated and complex relationships between the heat, power and raw materials used in their facilities and displacing fossil fuels would be very challenging and potentially costly. Furthermore, some of the temperatures, conditions and availabilities required by industrial processes could be difficult to achieve with renewable energy sources[5]. Therefore, the use of CCS in these sectors is seen as a necessary complement to efficiency gains and fuel switching to deliver the deep CO_2 reductions targeted by CEM governments.

3. Sectors considered

The 7 non-power sectors presented in Figure 1 are included in the scope of work of the CCUS Working Group. In addition, it is suggested to give consideration to the production of aluminium and food and beverages[6], due to their associated process emissions as indicated in Section 2 but accepting that CCS in these sectors is likely to be introduced later. The nine sectors, labelled according to the UN International Standard Industrial Classification, are listed in Table 1 along with their short names as used in this paper.

Table 1. ISIC Rev.4 classification of sectors within the scope of work

Sector	ISIC title	Short name
B.062	Extraction of natural gas	Natural Gas Processing
C.10 / C.11	Manufacture of Food Products and Beverages	Food and Drink
C.1701	Manufacture of pulp, paper and paperboard	Pulp and Paper
C.192	Manufacture of refined petroleum products	Refining
C.20	Manufacture of chemicals and chemical products	Chemicals
C.2394	Manufacture of cement, lime and plaster[7]	Cement
C.241	Manufacture of basic iron and steel	Iron and Steel
C.242	Manufacture of basic precious and other non-ferrous metals	Non-Ferrous Metals
Unclassified in Rev.4	Manufacture of biofuels (liquids and gases)	Biofuels

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[5] Some processes, for example, require constant heating rates and highly consistent fuel supplies.

[6] These sectors do not see CCS widely applied in IEA modelling of the 2050 timeframe (IEA, 2012), but could be suitable for CCS in certain locations.

[7] This paper does not consider the application of CCS to the manufacture of lime or plaster.

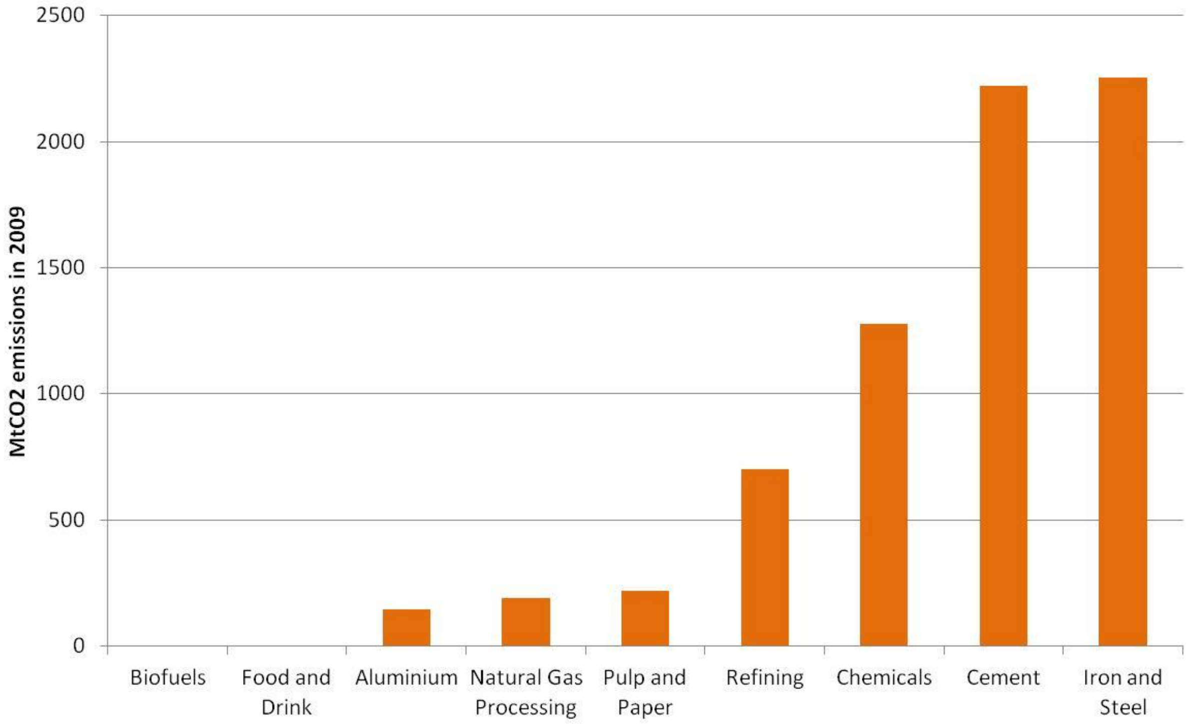

Figure 2. Emissions from the 9 sectors (IEA ETP 2012 figures)[8]

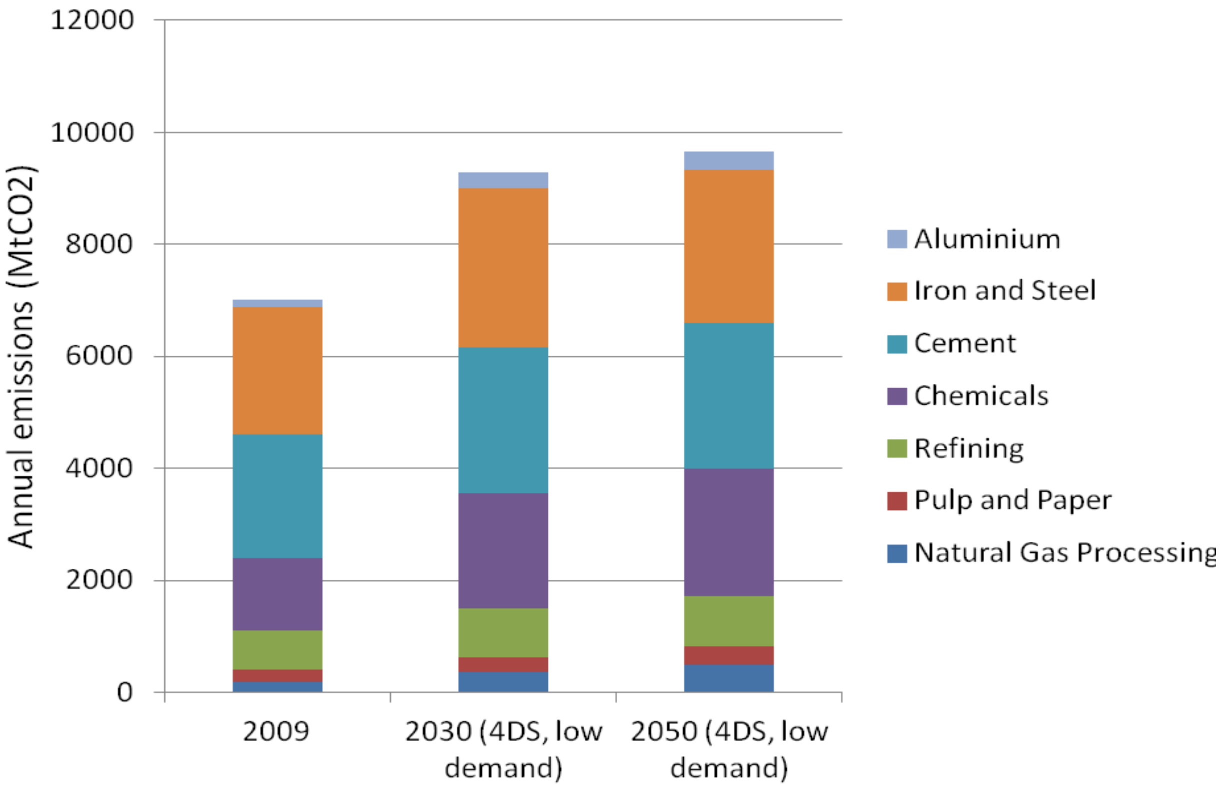

Figure 3. Emissions trends under the IEA Energy Technology Perspectives 4 Degree (low demand) Scenario

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[8] Note: Biogenic CO_2 emissions from the Biofuels and Pulp & Paper sectors are excluded due being considered to be net zero emissions in GHG accounting principles.

The emissions from these sectors represent 22% of total global CO_2 emissions[9]. Taking Figure 2 and Figure 3 together it can be seen that the contribution of some sectors to projected emissions in 2050 under current policy trends is much higher than others. Emissions from the chemicals sector, for example, may grow substantially due to increased output, and emissions from refining may grow due to the additional processing of heavier crude to meet demand for transport fuels, despite efficiency improvements. There is a pressing need to focus work on CCS in industrial applications on sectors that will benefit most from additional effort and attention. These sectors will be those that are:

- most likely make a high contribution to global CO_2 emissions in the absence of CCS
- facing technical challenges to the implementation of CCS that need to be tackled by collaborative effort in the near- to medium-term
- under economic and political pressure to reduce emissions in the near- to medium-term[10] whereby development of proven CCS solutions could reduce firms' risk from possible high future CO_2 prices, effectively capping their exposure at the cost of CCS and providing regions possessing CCS options with a competitive advantage.

Although the required level of effort for advancing CCS in other sectors may be lower – for example because capture of CO_2 from sources such as gas sweetening is straightforward and proven – their attractiveness from an emissions reductions perspective is not inferior, indeed in many cases it will higher, depending on location and cost factors.

Consequently, it is proposed that a subset of 4 out of the 9 sectors receive most of the attention from the CCUS Working Group.

- Refining
- Chemicals
- Cement
- Iron and Steel

These sectors are projected to increase their combined emissions by one third by 2050, and to be responsible for between 21 and 23% of global CO_2 emissions under current policies (i.e. due to emissions improvements elsewhere in the economy and the difficulties related to abating process emissions, the relative share of these four sectors is set to grow). They each face technical challenges, largely related to the capture of CO_2, which has different technological requirements to the power sector, and related to the integration of CCS processes on complex industrial sites. Furthermore, the four sectors are within the scope of existing climate mitigation policies and thus face the prospect of regulatory costs in proportion to their emissions intensities. The conclusion for all four sectors is that CCS will be essential for them to make substantial cuts in emissions and that they all have political and economic motives for developing the technology.

Table 2 summarises the rationale for prioritising the four sectors. The conclusion for all four sectors is that CCS will be essential for them to make substantial cuts in emissions and that they all have political and economic motives for developing the technology.

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[9] In tonnes of CO_2 equivalents in 2009

[10] The near-term is considered to be the period until 2020. Medium-term is considered to be 2020 until 2030. Long-term is considered to be 2030-2050 and beyond.

Table 2. Rationale for prioritising the four key sectors

Sector	Potential emissions profile without CCS	Technical challenges	Political pressures
Refining	Despite a projected decline in the share of petroleum products in transport in the coming decades, the absolute volumes of petroleum transport fuels are set to increase until at least 2030 and only reduce thereafter (by up to 50%) in scenarios achieving 450ppm by 2050. Without CCS refineries will continue to generate CO_2 from the production of heat, hydrogen and power, more of which will be required to satisfy the growing global demand for high quality transport fuels from potentially lower quality feedstocks.	Refineries comprise multiple sources of CO_2 from various processes. Different flue gas streams have different sizes and compositions, requiring different approaches to CO_2 capture. Furthermore, refinery configurations are themselves diverse, and use processes dictated by the scale, feedstock and desired product slate. Work is needed on the integration of CCS on complex refinery sites and the assimilation of multiple CO_2 streams.	Refineries are often on large sites that are significant point sources of CO_2. This brings them within the scope of GHG control policies that will increase refining costs. Several regions are developing policies to reduce the carbon content of transport fuels; this challenges the increasingly energy- and hydrogen-intensive processing required to produce higher proportions of transport fuels from feedstocks including oil sands and heavy bituminous crudes.
Chemicals	Manufacturing of ammonia, methanol and olefins are all expected to increase to meet rising demand for food, fuels and consumer goods. Without CCS, the associated emissions from the chemical sector could increase by 70-80% by 2050 due to inseparable process emissions and a continued reliance on fossil fuel feedstocks.	Chemical sites face many of the same challenges as refineries in terms of application of CCS. No two chemical sites are alike and each supports a range of processes and associated emissions. In addition, production of ammonia and methanol from coal is expanding, which raises the emissions intensity.	The chemical sector alone is responsible for almost a quarter of global GHG emissions and, whilst efficiencies are improving, production continues to increase strongly. The scale of emissions from the chemical sector makes it a focus for climate policies.
Cement	Cement production is accepted to be intimately linked to economic growth via the construction industry. Without CCS, emissions are projected to increase by between 15 and 30%. CCS is the only mitigation option for the process emissions from calcination of lime.	Broadly speaking, processes used in the cement industry are globally homogeneous and plant size is growing, which could greatly facilitate the application of CCS. However, although several CO_2 capture methods have been proposed and studied, none have been tested at a pilot scale in order to better understand process	As for the other sectors presented in this table, climate policies, if applied unevenly in different regions, could lead to costs that encourage the relocation of cement manufacture. The cement industry is approaching its limits for direct energy emissions reductions through fuel switching and efficiency measures,

		integration and costs.	assuming that best practice measures are adopted globally in the coming decade. However, process emissions improvements will remain a problem for the industry without CCS.
Iron and Steel	Without CCS, the iron and steel sector's CO_2 emissions are projected to rise by 17% on the basis of current polices, and up to 70% if business-as-usual continues. To meet 2DS targets, emissions could be reduced 40% by CCS and 25% by other methods by 2050 compared to the current policy trajectory. Given the scale of the sector and the anticipated increase in per capita steel production of 35-60%, there is an imperative for CCS.	Steel is produced by a number of methods that each have different configurations depending on region, raw material and fuel source. Studies show that CO_2 could be captured from blast furnaces and other processes, and options exist that would require different degrees of reconfiguration of the plant. Demonstration of different technology options to better understand technical optimisation and costs is necessary.	Increasing the burden of climate policy on a sector that is strategically important in many regions is a challenge in the absence of an effective mitigation option available at an accessible cost. Although global application of CCS in the iron and steel sector is not foreseen before 2030, the development time for new technologies means that progress would need to accelerate to meet even this target.

These four sectors lag behind the power sector in terms of understanding of the methodologies, potentials and incentives for the application of CCS to mitigate their CO_2 emissions. Annex IV shows that industrial applications that pose technical challenges for CO_2 capture – i.e. those that are not 'high purity' CO_2 sources and therefore straightforward to deploy as a CO_2 source for EOR – are not as advanced as the power sector in terms of scale of executed and planned projects. Work in the power sector has demonstrated that the lead times for developing the frameworks, techniques and infrastructure for deploying CCS can be in the order of decades. Scenarios indicate that CCS in industrial applications should not lag far behind the power sector; consequently, action in these four sectors should be prioritised today. It must not be forgotten that for these capital-intensive sectors, 2050 is only one investment cycle away and much capacity is due to be replaced in the next 10 years. The knowledge for understanding how to *prepare* these sectors for the later application of CCS is just as important as planning the future deployment.

The five other sectors within the overall scope of work but which are not prioritised are not considered to face the same scale of challenges in terms of CO_2 emissions reduction, technical development or political pressure. Annex III summarises these considerations.

A note on CO_2 capture processes

CO_2 emitted from industrial activities reaches the atmosphere as a result of fossil fuel combustion, oxidation of carbonaceous reducing agents or removal of CO_2 impurities from a production process. Preventing this CO_2 from reaching the atmosphere can be achieved in a number of ways, which, in the power sector have commonly been categorised as pre-combustion, oxy-combustion (or oxyfuel), and post-combustion CO_2 capture. However, this paper describes processes that do not fit comfortably into these categories. Firstly, the CO_2 emitted by industrial applications is often unrelated to fossil fuel combustion. Secondly, the concentration of CO_2 in the gas streams of industrial processes changes along a continuum and it is sometimes difficult to define a CO_2 capture technique as being directly comparable to, for instance, post-combustion CO_2 capture from a coal-fired power plant. If the concentration of CO_2 is below about 90% it is essential to know its partial pressure in order to identify how to remove/purify it most effectively. Figure 4 shows the partial pressures of CO_2 for a range of industrial processes.

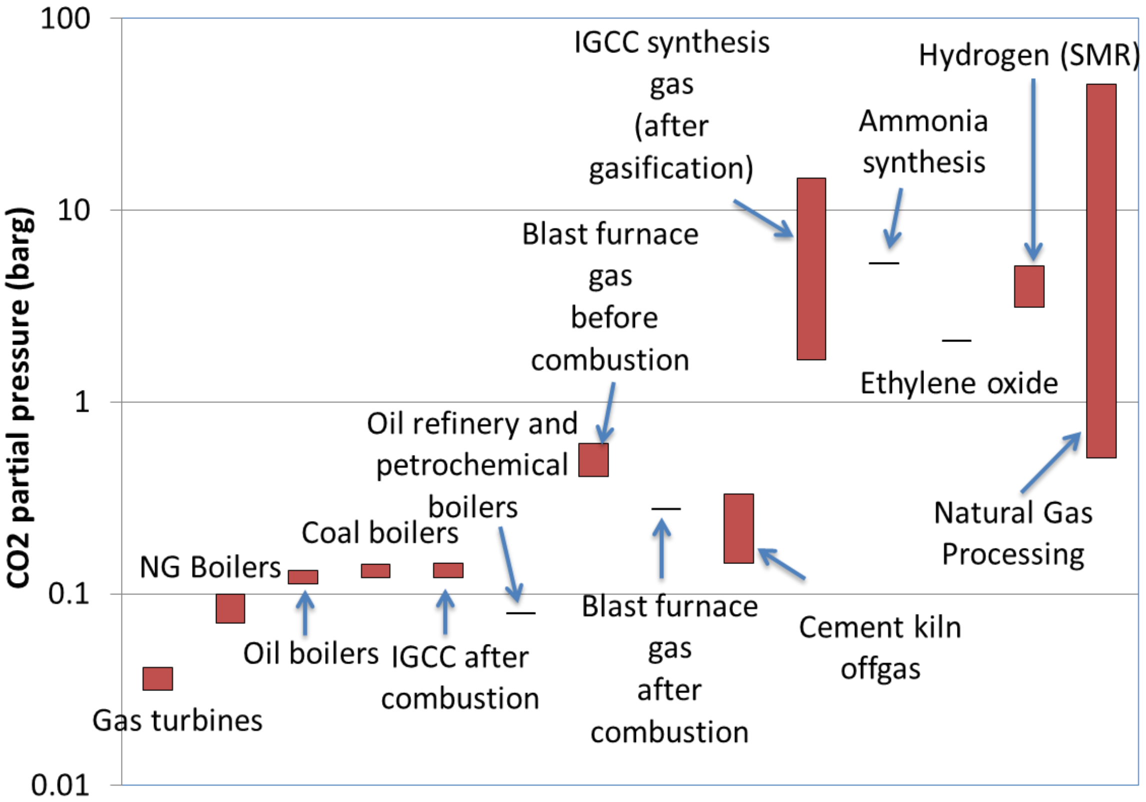

Figure 4. Concentrations of CO_2 (in partial pressure) from a variety of industrial applications and power generation sources (Fennell, 2012; Kaarstad et al., 2011)

It is the combination of the size of the CO_2 source, the overall process pressure and the partial pressure[11] of the CO_2 in the gas stream at the point of CO_2 capture that are the key variables for identifying the appropriate approach to CO_2 capture. In general, the larger the size and the higher the partial pressure, the greater the ease of capture and the lower the cost per tCO_2 captured and stored. CO_2 sources at similar partial pressures can be captured using similar approaches and so present opportunities for technology learning between sectors. It should be noted, however, that additional variables, such as technological maturity, ability to capture higher proportions of onsite emissions or ability to direct multiple

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[11] Partial pressure is often a more accurate indication of capture feasibility for CO_2 in a flue gas stream than concentration. This is because a flue gas containing 15% CO_2 that is exhausted at a high pressure can have its CO_2 removed much more easily than the same flue gas at low pressure. Partial pressures indicate the pressure of the CO_2 component in the gas and thus reflect both pressure and concentration.

CO_2 streams into one CO_2 capture plant, might influence the ultimate choice of approach to CO_2 capture.

In this paper the following generic types of CO_2 capture are described, and could be applied equally well to any industrial process, including power generation:

- Flue gas scrubbing. The CO_2 is removed from the flue gas stream that leaves the industrial process. The CO_2 is generally at low partial pressures (up to 0.2 bar) Some treatment of the flue gas may be required before CO_2 capture, for example removal of SOx and NOx impurities. Post-combustion capture from power plants would fit into this category.
- Oxy-firing. The industrial process itself is adjusted to yield a flue gas that is richer in CO_2 than before the adjustment was made. For many processes this requires a considerable redesign of the process and a supply of oxygen into the boiler, furnace, or kiln, usually from an air separation unit (ASU). Oxy-combustion for power plants would fit into this category.
- Upfront carbon removal. Some processes that use fossil fuels as either a fuel or a reducing agent can also be operated with hydrogen, which is carbon-free. The hydrogen can be supplied by reforming or gasifying the fossil fuel in advance of running the process and capturing the CO_2. Separation of the hydrogen leaves a CO_2 stream that is highly concentrated and can generally be easily purified.
- Process emissions clean-up. Some processes, such as natural gas sweetening, fermentation or smelting, generate a highly pure CO_2 process emissions stream as a by-product. This CO_2 is at a sufficiently high concentration to be purified using simple techniques. Pre-combustion capture from power plants would fit into this category.

Within each of these families of CO_2 capture are processes that could be appropriate for quite different capture techniques, depending on volumes, impurities, and other factors. Several groups of capture techniques can be identified:

- Absorption solvents. Currently the most suitable capture technique for flue gas scrubbing at low partial pressures and high volumes of flue gases due to low CAPEX requirements. Aqueous solvents such as amines and chilled ammonia fit into this category. Energy required for regenerating the solvent and separating the chemically bound CO_2.
- Solid adsorption. Currently the leading technology for the separation of high purity hydrogen from CO_2, for example in upfront carbon removal. This includes pressure swing adsorption (PSA) and vacuum swing adsorption (VSA). Due to the energy requirements of compression, PSA is usually considered suitable for high concentrations of CO_2. However, the resulting CO_2 stream from PSA is not high purity and must be cleaned up using, for instance, a liquefaction process.
- Physical adsorption. Can be applied to process emissions clean-up or flue gas scrubbing and is commonly used to remove hydrogen sulphide and CO_2 from natural gas streams and refinery processes. More selective than absorption solvents. Sorbents include methanol and dimethyl ethers. Energy required compression and refrigeration of methanol.
- Cryogenic rectification and Liquefaction. Separation of impurities from high concentration CO_2 streams by temperature-induced phase change.
- Membranes. Currently in operation for natural gas sweetening, but not yet

commercialised for other large-scale CO_2 removal applications, membranes offer low-energy, simple CO_2 removal possibilities but need to be proven at higher pressures and to be robust against impurities.

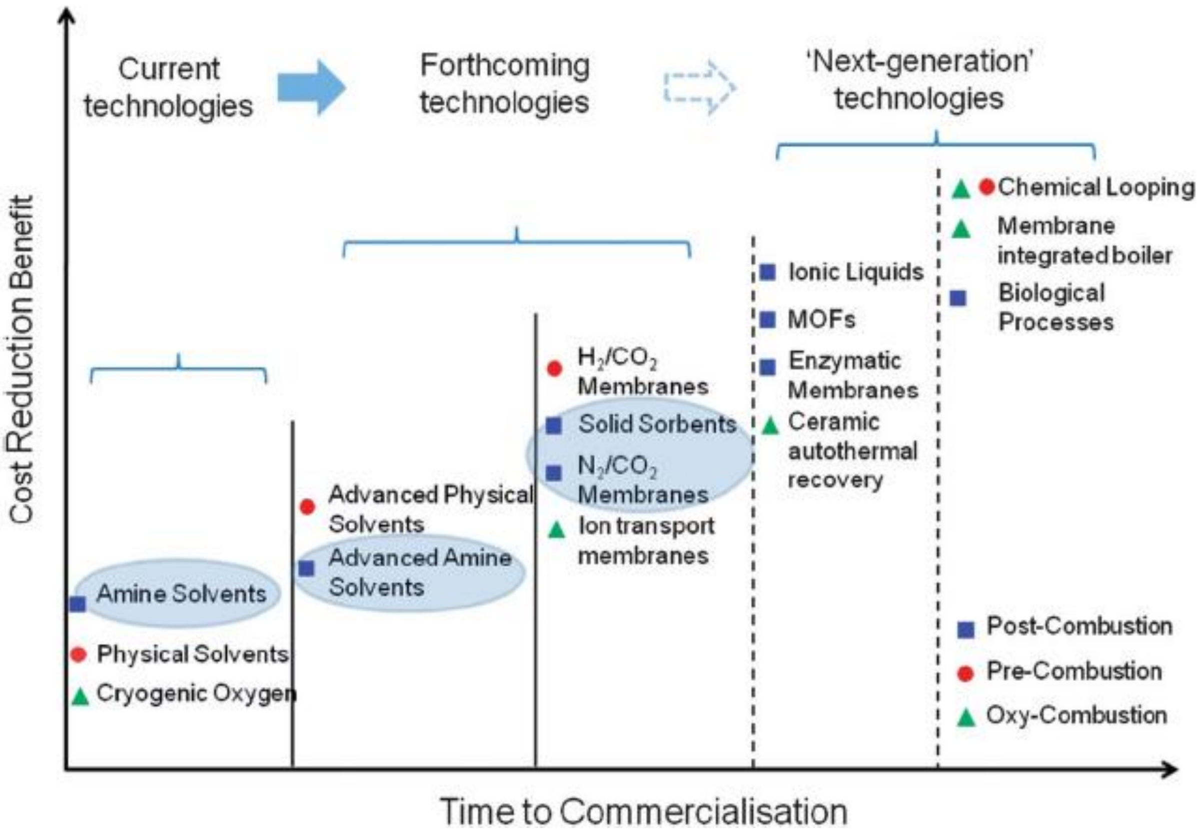

Figure 5. Representation of different phases of CO_2 capture technologies under development for power generation (Zhao et al., 2012)

Due to the wide range of CO_2-containing gas streams from industrial applications, and the many opportunities for redesigning processes to enhance CO_2 capture, the optimal solution for a particular capture type may be found on a case by case basis and could involve combinations of the techniques listed above.

In addition to the varying political importance of climate mitigation in certain sectors, industrial applications of CCS present a range of different costs, which arise from the technical challenge related to the CO_2 concentration (partial pressure) in the flue gas and from the scales of the industrial plants. In recognition of this, this paper seeks to summarise existing knowledge on the types of processes that present a sufficiently large stream of CO_2 and the challenges for applying CO_2 capture to them. Going further, it considers each CCUS AG country and assesses the potential relevance of CCS in the four sectors in these countries. The following assumptions are used:

- The relevant minimum CO_2 capture level from a source for the first phases of CCS deployment is considered to be less than 500 ktCO_2/yr, after subtraction of any CO_2 that is utilised in further processes or sold 'over the fence' to other commercial processes. As regional CO_2 'clusters become developed later, smaller sources will be able to overcome these limits to economies of scale and apply CCS at low cost. In fact, some of these sources may find it necessary to apply CCS to achieve emissions reductions in future decades.

- CO_2 from existing higher purity sources[12] present ideal early opportunities for integrated CO_2 capture, transport and storage, and will be low-cost emissions avoidance options that will be deployed before higher cost capture options.
- CO_2 in flue gases at lower partial pressures (partial pressures below 1 barg in Figure 4) requires either additional energy (for solvent regeneration, compression, cooling or oxygen production) or reconfiguration of the process to raise the partial pressure level. Sites without excess heat will require the provision of an additional heat source onsite, either via an additional boiler or imported electricity.

4. Iron and Steel

It is estimated that in 2009 the iron and steel sector emitted 2.3 $GtCO_2$/yr in the production of 1.2 Gt crude steel (IEA, 2012)[13]. Steelmaking was the single largest industrial source of CO_2. Steel production, according to forecasts, could almost double by 2050 because the consumption of steel is closely linked to economic development. In general, economies follow an inverse U-shaped curve of steel-use intensity, whereby the rate of steel consumption per unit of GDP increases rapidly as the economy becomes more mechanised and construction expands; this rate then declines to a peak before falling off and becoming characteristic of mature and increasingly service-based economies (Warell and Olsson, 2009)[14]. Figure 6 shows that China’s rate of steel development is much faster than the rate of more mature economies when their per capita GDP was at China’s present level.

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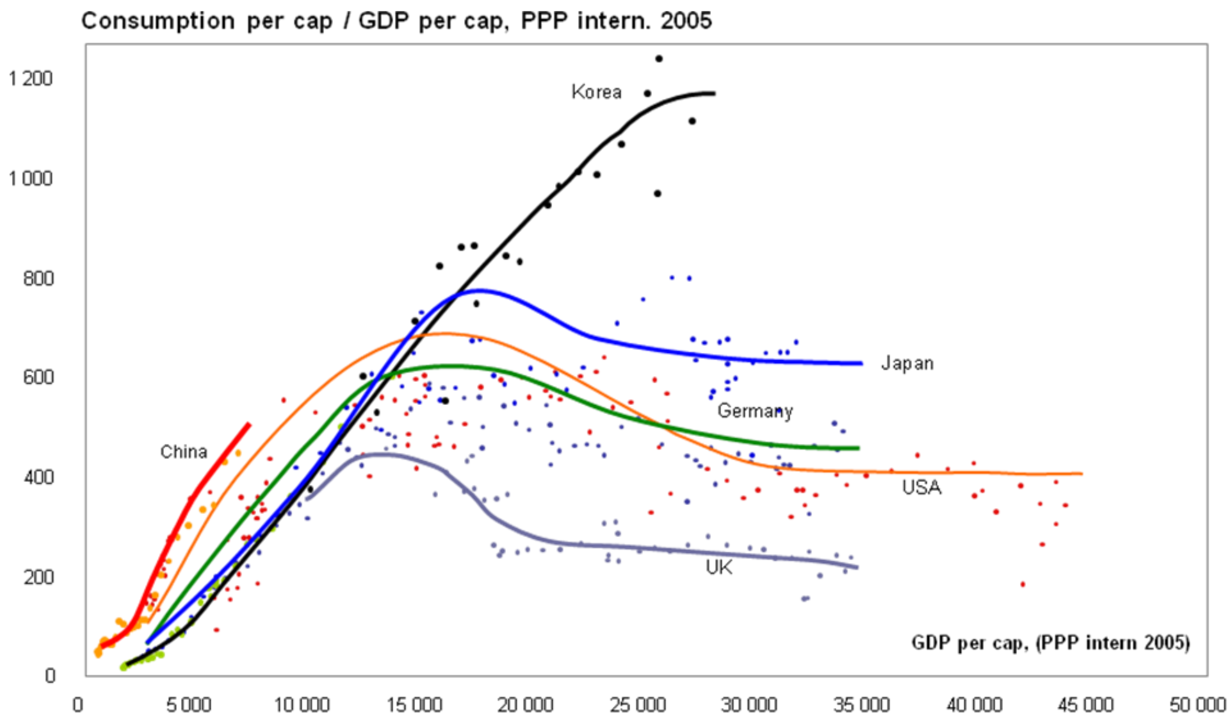
[12] In some publications processes that do not present a technical challenge or additional energy costs for capturing CO_2 (concentrations of over 80%, to the right in Figure 4) are grouped together (e.g. IEA/UNIDO, 2011). These processes generally involve: the gasification of fuels to produce synthesis gas or hydrogen, the separation of contaminant CO_2 during gas clean-up and the production of hydrogen via steam methane reforming. Since one of the purposes of this work is to understand the challenges facing individual sectors and the firms that are active in them, it has been decided not to follow this approach, but to allocate these processes to the sectors to which they contribute as follows:

- Gas-to-Liquids (GTL) is included in Refinery
- Hydrogen production from natural gas (for non-refinery purposes) is included in Chemicals
- Gas processing is included in Natural Gas Processing
- Ammonia production is included in Chemicals

[13] Direct emissions (not including indirect emissions from imported power consumption)

[14] Taking into account changes in technology and material substitution in the economy.



Source : WorldSteel, Worldbank, Laplace Conseil analysis

Figure 6. Relationship between steel consumption per capita and GDP per capita (Laplace Conseil, 2012)

Figure 7 gives an indication of how steel production might evolve globally[15]. Note that because steel is traded as a global commodity, production projections do not reflect only internal consumption, for instance in a country's construction or automobile industries, but also exports of steel and products in which it is embodied.

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[15] This increase in steel consumption is predicted despite the increasing opportunities for material substitution. Steel is likely to feel pressure from aluminium for the construction of vehicle bodies, especially if vehicle cost and fuel cost become more closely linked in purchase decisions, but lifecycle emissions may not always be improved. High performance polymers have the potential to substitute steel in many construction and engineering applications. In most applications where steel is replaced, there is environmental benefit related to weight reduction or resource intensity of production. It is expected that substitution will moderate growth in the sector but not cancel it out, especially if lightweight steels are successfully developed.

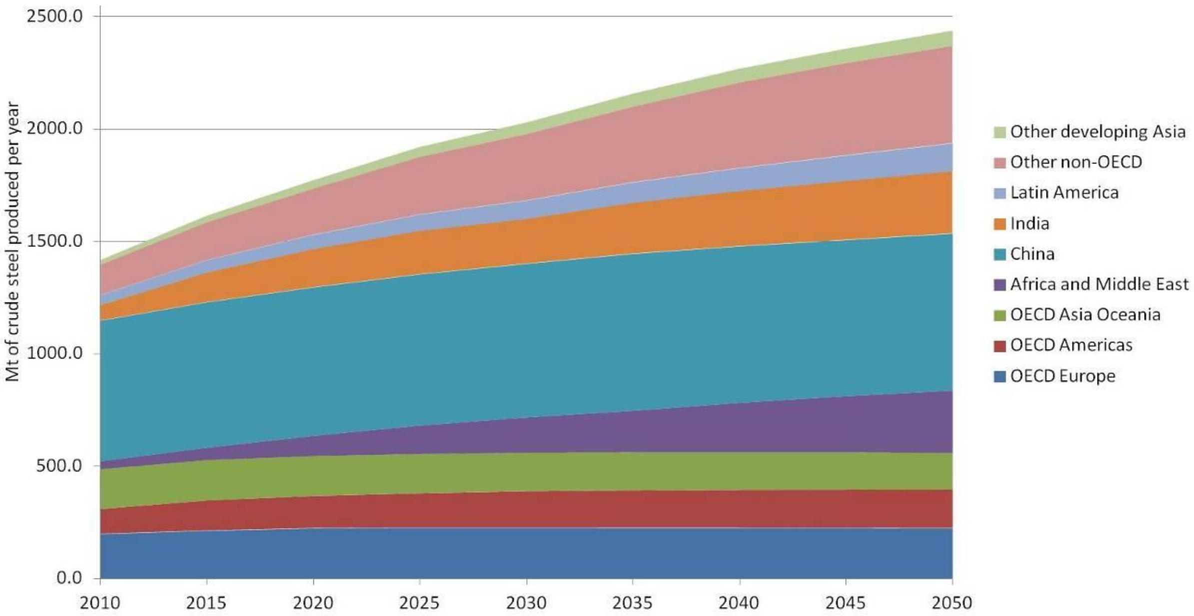

Figure 7. Crude steel production to 2050 (IEA Energy Technologies Perspectives 2012, low demand scenarios)

Efficiency improvements in the steel industry have delivered significant gains in recent years. Figure 8 shows the impact of efficiency improvements in Germany. Notwithstanding the recent rise in specific emissions, it also shows that the industry is approaching theoretical limits to reducing combustion emissions in existing technologies, and that process emissions leave a residual level of CO_2 intensity that cannot be mitigated through efficiency measures or fuel substitution alone.

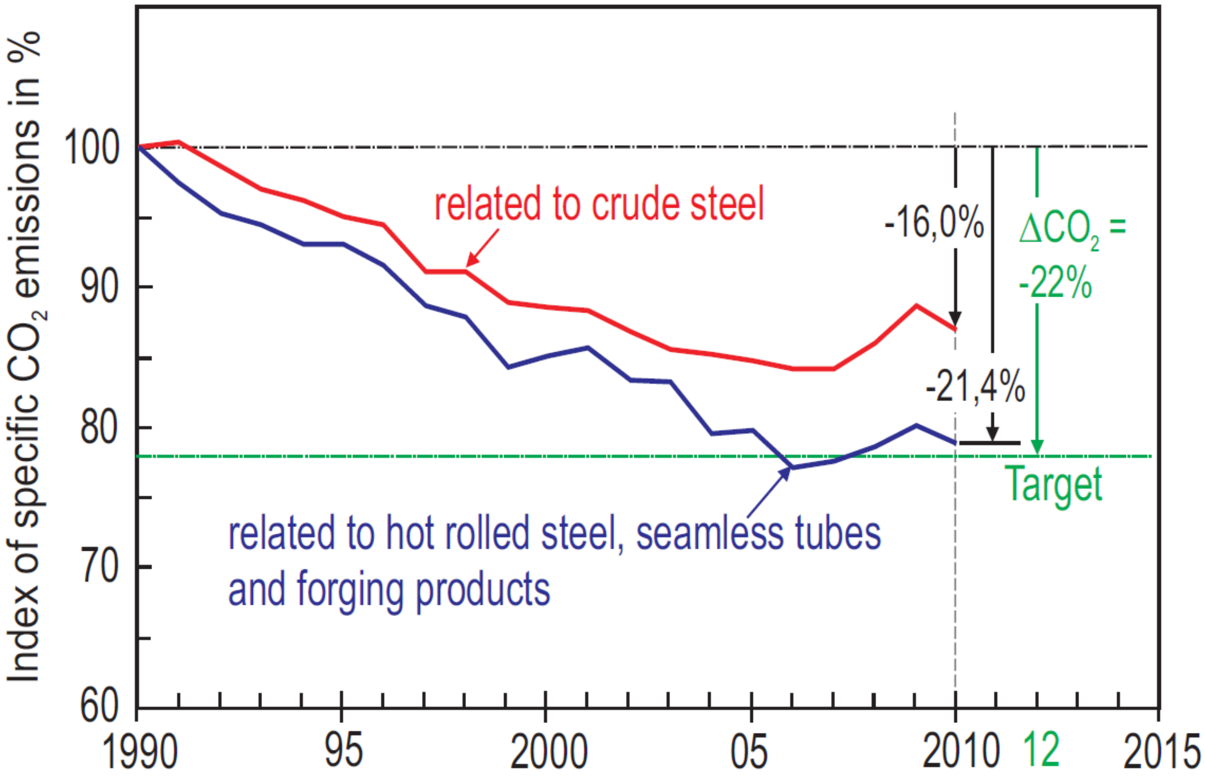

Figure 8. CO_2 intensity of German steel production, with 1990 as base year (Stahl, 2012)

The 1.51 Gt of crude steel produced in 2011 were produced predominantly by the blast furnace (BF) plus basic oxygen furnace (BOF) route (Figure 9). The blast furnace route is one of three main routes to steel production. The main technologies have changed little in the last thirty or forty years, but efficiencies have gradually improved and plants have dramatically increased in size. Figure 10 shows one projection for the technology shares that is used in the IEA scenario with ambitious CO_2 emissions reductions. The potential of the main steel-production routes to apply CCS is discussed in the following technology summaries.

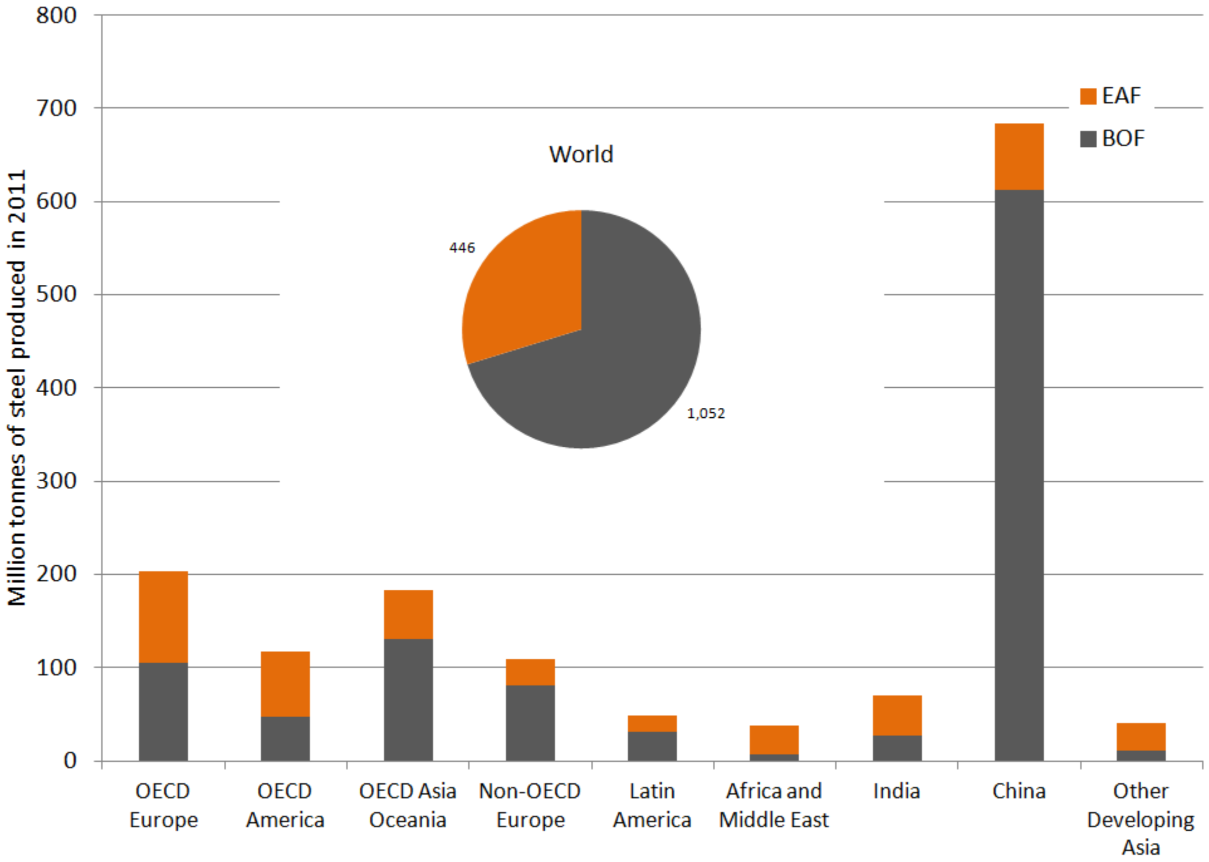

Figure 9. Steel production in 2011 in Mt of crude steel (WorldSteel, 2012)

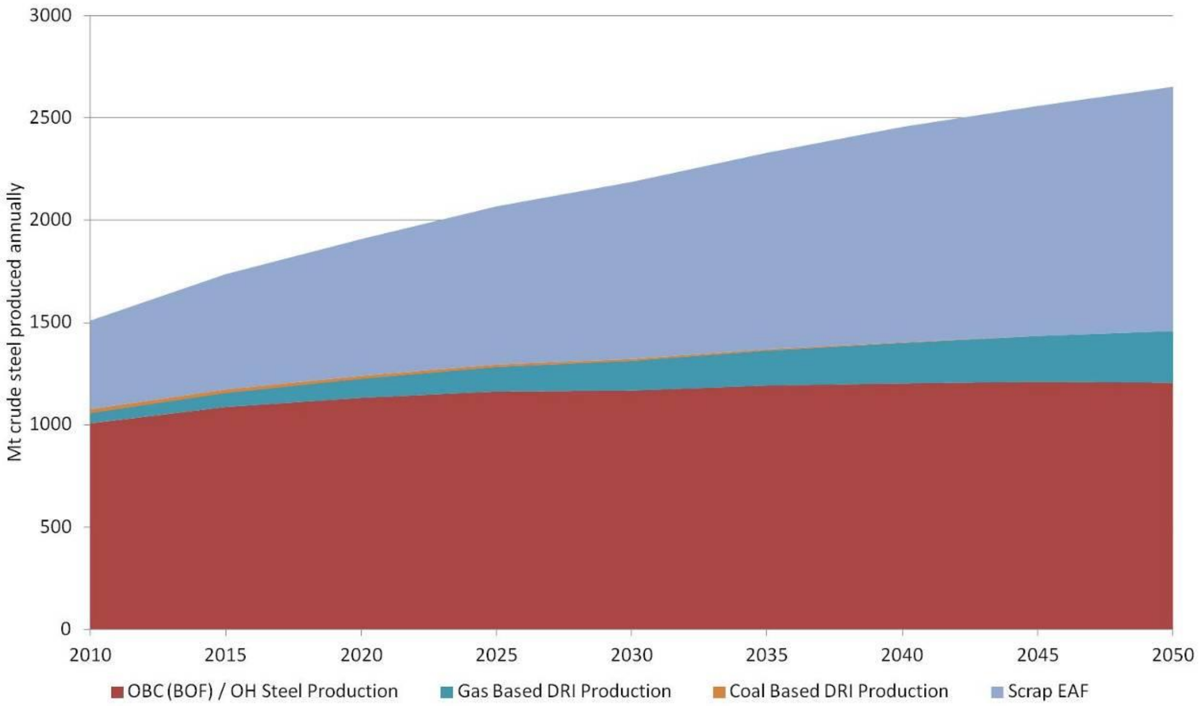

Figure 10. One scenario for future shares of steel production technologies to meet 2°C climate reduction targets (IEA ETP 2DS low demand scenario)

Technology summary: BF/BOF	
In brief	BF smelts iron ore into pig iron. Hot air reacts with coke at 900 to 1300°C to produce the carbon monoxide that reduces the iron ore to make iron. The CO_2 from the reduction process is released at the top of the furnace in the BF gas. At an integrated steelworks the molten ‘pig’ iron is combined with around 20% scrap steel and blown with pure oxygen in the BOF to form steel. BF gas is usually used to supply heat to other parts of the plant and/or generate electricity. Coal generally provides about 95% of energy consumed in coke and heat production, but natural gas can be used marginally for BF injection.
New technologies	1. In oxygen blast furnaces (OBF) the hot blast gas has increased oxygen content and replaces some of the coke feed with coal. This increases the CO_2 content of the flue. 2. Partially pre-reduced iron ore can be injected into the blast furnace, lowering energy consumption, but this would be in competition with other uses of pre-reduced ore. 3. Coke oven gas can be used as a feedstock for methanol production; something that is already commercialised in China. 4. CO_2-containing BF gas could be sent to a gas-fired power plant configured for low calorific gas fuel and equipped with CO_2 capture (Kapteijn, 2010).
Trends and regional differences	• BF/BOF route is likely to persist as the dominant route. New plants can be very large (12 Mt hot metal/yr or more) and it is unlikely that new blast furnaces will be built in Europe. In fact, closures in Europe and the United States will continue according to current trends as necessary capital-intense refurbishments are difficult to

	finance. New BFs are mostly being built on a very large scale in Republic of Korea, China, India and other countries in Asia. • There is a trend towards reducing coke consumption through utilisation of the carbon monoxide-BF gas as a reducing agent in the furnace. Evidently there is increasing competition for the efficient use of the BF gas, which has value, and would not be available if CO_2 were scrubbed directly from the flue gas.
CO_2 partial pressures/ concentrations	BF flue gas contains between 20 and 23% CO_2 and BOF flue gas contains 34% CO_2 (Tobieson, 2011) but their availability for capture is a highly site-specific issue related to the extent that these gases are used as fuel on site. A combined stream of coke over gas (COG) and BF gas has been found to have 23% CO_2 (Wiley *et al.*, 2011). Other CO_2 sources onsite would be likely to contain between 10 and 16% CO_2, with the exception of the flue from coke oven gas combustion if this were used for power or heat generation, which would be around 4% CO_2. However, the flue gases from power generation and hot stoves burning blast furnace gas, coke oven gas and converter gas have been considered to contain 28% CO_2 (Arasto *et al.*, 2012).
Applicability of CCS	• BF and BOF gases are suitable candidates for flue gas scrubbing using absorption solvents such as amines or chilled ammonia (Ahn, 2011). • Redesign of the BF to allow firing with increased oxygen and 'top gas recycling' (TGR) is proposed as a more holistic solution that would provide an almost pure stream of CO_2. The recycle of carbon monoxide from BF gas into the furnace reduces coke consumption, which is very attractive to companies that currently face a tight market for metallurgical coal. However, it removes the availability of BF gases for on-site heat and power production whilst simultaneously increasing the power and heat demand for cooling and compression. A standalone CHP plant could be considered if no local excess heat was available and, if natural gas were used, the overall energy consumption of the plant would in fact be reduced compared to a benchmark BF without CCS. Alternatively, a sorbent for which waste heat would be sufficiently hot to regenerate the solvent could be attractive as it would avoid the need for additional heat. Chilled ammonia is on such option but would require electricity inputs for chilling.
Likely requirement for additional heat	High (if flue gas scrubbing using currently available absorption solvents were used). Studies have found that solid sorbent methods, such as pressure swing adsorption, could have advantages over chemical solvents when dealing with CO_2 concentrations above 20%, with benefits to PSA increasing at higher partial pressures (Birat, 2010). It is thought that the lowest cost option for the TGR process would be to use pressure swing adsorption (PSA), which yields a CO_2 stream of 80% to 85% and then purify this further using chilled distillation at high pressure. While this is a high cost capture approach, it can remove the need for further compression and result in a favourable energy balance

	overall.
Capture potential	Approximately 50% of onsite emissions. Up to 80% for future smelting routes (Meijer, 2011).
Size of CO_2 source	CO_2 intensity is 1.45 (best available technology) to 2.3 (global average) $MtCO_2$/t crude steel (Birat, 2010; Wiley *et al.* 2011). Plant sizes are 1.5 (small) to 17 (Shanghai Baosteel, comprising four BFs) Mt steel/yr. Therefore, small sites produce 2 $MtCO_2$/yr, but integrated sites can have up to 10 different smokestacks (Birat, 2010). In general, new sites have two trains with BF capacities of 3 to 5 Mt steel/yr each, giving 4 to 7 $MtCO_2$/yr. At 50% capture, 0.5 $MtCO_2$/yr could be captured from a 1.5 Mt integrated steel mill. Capture of over 6 $MtCO_2$/yr from very large new integrated steel mills would be larger in scale than a 1 GW CCS-equipped coal-fired power plant and would thus need to be situated with access to a sufficiently large CO_2 storage site.

Technology summary: DRI/EAF	
In brief	Direct reduced iron (DRI) is produced from the reduction of iron ore with a reducing synthesis gas (made from natural gas or coal) at 800 to 1050°C. DRI oxidises easily and must be quickly processed into steel on an integrated site. The DRI is generally mixed with scrap steel before treatment with oxygen in an Electric arc furnace (EAF) at 1800°C to produce crude steel, often suitable for speciality purposes.
New technologies	• ULCORED is a process developed to optimise the application of CCS to DRI and to reduce the natural gas consumption. It has not yet reached pilot stage. • The IMTK process is coal-based and produces pig iron nuggets that are easier to transport than DRI. It has an energy saving compared to coal-based DRI and is currently operational at 0.25 Mt/yr.
Trends and regional differences	With the exception of China, there is a worldwide tendency towards EAF plants, which can be shut down and started up quickly. DRI/EAF is more popular in countries without large enough quantities of available scrap to meet demand, with low availability of coke, and/or where natural gas is relatively cheap and abundant. DRI is predicted to see the greatest growth rates of all routes up to 2020 but will not rival the others in absolute terms. DRI/EAF is economic at much lower scales that BF/BOF and has lower capital costs. DRI/EAF ‘minimills’ are commonly constructed in India and other developing countries based on coal, which places them among the most CO_2 intensive steel plants. DRI/EAF is currently more expensive than BF/BOF at large scales.
CO_2 partial pressures/ concentrations	The production of reducing/synthesis gas produces a high purity stream of CO_2 by gasification, steam reforming or catalysis.
Applicability of CCS	CO_2 could be captured from the reducing gas production step if the plant were large (larger than many minimills). The EAF power source could be equipped with CCS if it were sufficiently high volume, using technologies under development for the power sector.
Likely requirement	Low. The CO_2 from DRI production is a relatively pure source and could

for additional heat	be cleaned up using amine or PSA processes without high levels of additional heat demand. Additional energy would nevertheless be need for CO_2 compression.
Capture potential	Applying CCS to DRI/EAF could reduce direct emissions from the DRI production steps by 68%. If the power for EAF was produced onsite (scales of up to 150 MW) and CCS applied to power production, emissions could be reduced by 70% to 75% overall.
Size of CO_2 source	Coal-based DRI has a CO_2 intensity of 2.5 tCO_2/t hot metal (Newman, 2011), and natural gas-based DRI is around 1 tCO_2/t hot metal. The EAF step has an intensity of 0.3-0.6 tCO_2/t hot metal, giving an overall intensity of around 3tCO_2/t for coal or 1.5 tCO_2 for natural gas. The world's largest DRI plant in Saudi Arabia using natural gas is 1.8 Mt/yr, which could represent a potential CO_2 stream of over 1.5 $MtCO_2$/yr from just the DRI production steps with 85% capture. A plant with a capacity of at least 0.7Mt/yr could capture over 0.5 $MtCO_2$/yr. Minimills of 0.2-0.4 Mt/yr would likely be too small for CCS unless local CO_2 transport and storage was available at low cost.

Technology summary: Scrap/EAF	
In brief	At around 60%, steel is one of the most recycled materials in the world (UNEP, 2011). Electric arcs are used to melt scrap steel before it is refined with oxygen, which removes impurities as oxides in slag. DRI is occasionally added to the scrap for chemical balance. EAF produces a range of steels, including high quality engineering and stainless steels, although purely scrap based steel is generally less high quality. The electricity consumption is 100-500 kWh/t hot metal depending on use of pre-heating (Birat, 2010; Entec, 2006). The major fuel use is for electricity generation, but natural gas (or coal-based synthesis gas) is used as a reducing agent and fossil fuels are usually used to provide additional heat and cast the metal.
New technologies	Efficiency can be increased by recovering hot exhaust gases and using it to preheat the scrap before it is melted.
Trends and regional differences	EAF minimills are currently more attractive to investors as they are lower capital projects and are increasingly producing grades of steel traditionally made by the BF/BOF route. However, there is only enough scrap steel to provide one third of global production (global recycling rates are 70% today) (Newman, 2011). This route is favoured by regions with available recycled steel.
CO_2 partial pressures/ concentrations	EAF produces off gases that contain carbon monoxide, CO_2 and volatile compounds (mainly process emissions). This gas can be used for pre-heating of the scrap. Technically, clean-up of the hot exhaust gas could provide a high purity CO_2 stream in addition to a fuel.
Applicability of CCS	At 0.3-0.6 tCO_2/t hot metal, CO_2 levels from EAF are already sufficiently low to comply with any existing or likely future benchmarks. CO_2 could be captured from power plants using technologies developed for the power sector.
Likely requirement	Capturing the process emissions from EAF would not require large

for additional heat	amounts of additional heat (depending on whether a shift reaction was used). Compression would add only incremental electricity consumption. The main impact could be the non-availability of off gases for pre-heating thus increasing overall energy consumption.
Capture potential	100% of process emissions. 90% (~88% avoided) of power emissions if CO_2 captured from an onsite fossil fuel-fired dedicated power plant.
Size of CO_2 source	Process emissions: 0.07-0.3 tCO_2/t steel, depending on DRI added to scrap. If 100% of process emissions were captured, a 2 Mt/yr plant could be technically suitable for CCS. However, since the world's largest EAF plant is only capable of producing 3 Mt/yr, CO_2 capture from scrap/EAF look less attractive than from other routes.

Technology summary: Smelting Reduced Iron	
In brief	The principle is akin to that of a blast furnace, but using coal instead of coke. Iron ore is reduced in a pre-reduction unit to produce a product similar to DRI that is smelted and further reduced in a vessel where coal is gasified to produce a heat and a carbon monoxide-rich hot gas. The heat is used to smelt iron and the hot gas is transported to the pre-reduction unit to reduce the iron oxides that enter the process. To optimise the reduction process, the carbon monoxide-rich gas can have its CO_2 content reduced to a low level through a clean-up step (for example, 3% CO_2 for the FINEX process). Smelting removes the energy-intense coking step and can utilise coal (or natural gas) that is not metallurgical grade and therefore generally lower cost. The FINEX process can use iron ore fines, which are abundant and this lowers the raw material cost. Smelting technologies are currently at the early deployment stage at commercial scales of up to 1.5 Mt/yr.
New technologies	The HISARNA process is under development by the ULCOS consortium and has the potential to significantly reduce CO_2 emissions from the smelting process by reducing the coal input or fuel switching to natural gas or biomass. HISARNA has been tested at 60 kt per year.
Trends and regional differences	It is likely that smelters will aim for the same levels of scale as BFs, especially in areas of high demand. Thus, smelting sites with 2 trains of 3-5 Mt hot metal output could be expected in the next decade if this route is successful. The MIDREX process uses natural gas, which can make it attractive in the Middle East.
CO_2 partial pressures/ concentrations	High. Although details of these processes are unavailable, the CO_2 stream would be likely to have high purity.
Applicability of CCS	CO_2 capture of a CO_2 stream from a smelter would not present any technical difficulties. Processes that include a CO_2-removal clean-up step of the hot gas are already effectively capturing CO_2 that could be compressed and dehydrated if necessary.
Likely requirement for additional heat	Low, especially if CO_2 were already being removed from the process.
Capture potential	A high percentage (over 90%) of the emissions from a smelter could be captured.

Size of CO_2 source	The CO_2 intensity of smelting processes can vary widely but is below that of the BF/BOF route. Large smelters (above 3 Mt/yr) would be likely to have emissions of over 1 $MtCO_2$/yr that could be readily captured. If two trains were operational on the same site, as is common with BFs, the captured CO_2 would be twice this amount.

Technology summary: Electrolysis	
In brief	Iron ore is separated into iron and oxygen by dissolving the ore in a soda electrolyte at 110°C or in a molten oxide electrolyte at 1600°C and applying an electric current. There are no CO_2 process emissions and a low level of emissions from heat production. Electrolysis could potentially be integrated with electricity production from solar, nuclear or hydro.
Trends and regional differences	No steel is currently produced by this method but the concept has been proven at lab scale. Commercialisation envisaged for mid-century.
Applicability of CCS	No need for CCS.

Technology summary: Hydrogen reduction	
In brief	Instead of using carbon-based reducing agents (coke, coal or natural gas), iron ore could be reduced by using hydrogen as a reducing agent, and forming water as the main process emission. Hydrogen production from natural gas or coal produces CO_2, which could be captured. Considerable redesign work would be necessary to enable the furnaces to operate with hydrogen and at elevated temperatures. Hydrogen production from electrolysis produces no CO_2, but commercial deployment of this technology in combination with zero-carbon electricity is considered decades away.
Trends and regional differences	No steel is currently produced by this method but the concept has been proven at demonstration scale. Commercialisation not envisaged before mid-century due to sufficient cheap hydrogen not being available.
Applicability of CCS	No need for CCS.

CEM CCUS AG country relevance

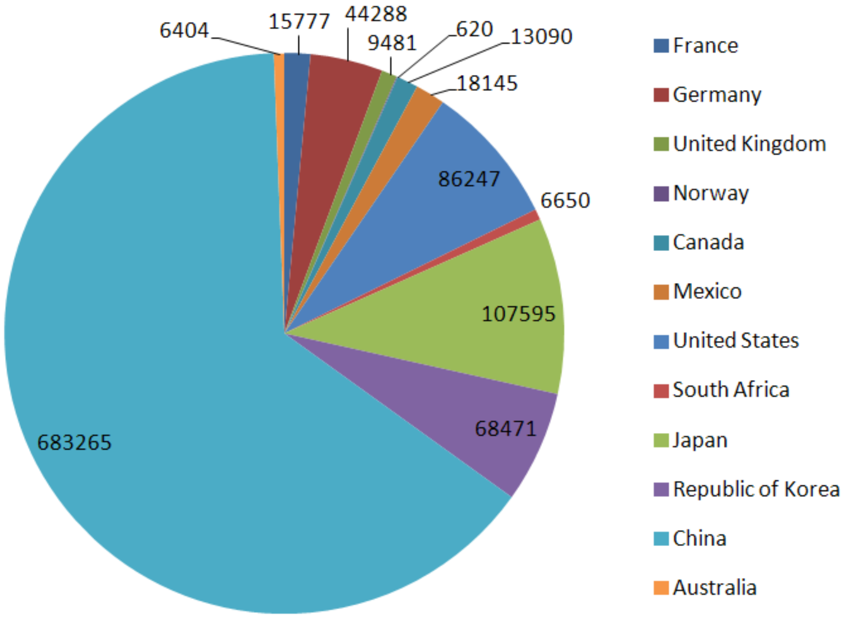

Figure 11. Steel production in CEM CCUS countries in 2011 in Mt crude steel (WorldSteel, 2012)

Australia

Production in 2011 was 6.4 Mt steel, 80% of which was from BF/BOF. Australian steel production has suffered from a loss of competitiveness in the region due primarily to the strong Australian dollar's impact on coal prices and steel export prices. Production has declined by over one third since the late nineties and the industry is squeezed – as was evident from Bluescope's plant closure in 2011 – with government policy unlikely to intervene sufficiently to support all of the current capacity. However, under current proposals steel producers would be able to claim back 94.5% of the AUD 23/tCO_2 cost of carbon taxing on average.

Activities: CSIRO's CO_2 Breakthrough in Metal Production Program (AUD 10 million over 4 years up to 2010, 60% of which is government funding) aims to prove the utilisation of heat from slag cooling to reduce energy intensity and the use of biomass in the iron and steel industry.

Canada

Steel is produced at thirteen plants in five provinces, six of these are in Ontario. In 2010, 13 Mt of crude steel were produced, and 6.9Mt were exported while 8.7 Mt were imported, primarily from the United States. The high value of the CAD and the economic crisis has contributed to temporary plant closures and an increase of imports, and structural changes in the global industry make a return to pre-crisis production levels uncertain. 58% of the steel produced in Canada in 2011 was BF/BOF, and the EAF steel was predominantly from scrap with a small contribution from gas-based DRI/EAF (WorldSteel, 2012).

Activities: The Canadian Steel Producers Association received CAD 0.3 million in government funding to contribute to World Steel's CO_2 Breakthrough Programme and has considered cogeneration and biomass utilisation approaches. There are no CCS projects in the sector.

China

China is the world's largest producer of steel (46%). In the last decade 90% of global capacity growth has been in China but this unprecedented rate of growth is now slowing and an absolute peak is predicted before 2020. The current focus is on raising profitability which has declined due to overcapacity (combined with a decrease in exports) and an increased cost of iron ore (due in part to the strong AUD). The industry is highly fragmented, with many small producers. Although growth in production is expected to continue, the rate of growth is expected to halve and there is a focus on mergers and acquisitions and the closure of older smaller plants for environmental reasons (KPMG, 2011). Currently, production is 90% by BF/BOF route, and although steel from scrap makes up only 14% of the total, this is projected to grow to 20% by 2015 (WorldSteel, 2012; Yun, 2012). The government's 2009 Outline for the sector has three objectives: major industrial restructuring based on subsidies and loans to support technological research and upgrading; foreign acquisitions by domestic steel enterprises; and reduce capacity to 500Mt. The current targets for energy intensity in the Chinese economy are a 16% reduction in energy consumption and a 17% reduction in CO_2 emissions per unit of GDP between 2011 and 2015. Energy intensity could be aided by a growth in Scrap/EAF when the recent boom in steel use will lead to a greater availability of recyclable material, but steel used in the construction sector may take another 3-5 decades to become available as scrap. A consideration for the Chinese steel sector will be how to incorporate an abundant supply of scrap steel – scrap availability could meet almost all Chinese demand in scenarios in which overall production declines by the 2030s – into a steelmaking infrastructure that is overwhelmingly based on the BF/BOF route.

<u>Activities</u>: There are no ongoing CCS activities or projects in the Chinese iron and steel sector.

France, Germany and the UK

Production of crude steel grew in 2011 by 8.9% (France), 25% (Germany) and 5.3% (UK) in response to economic recovery worldwide (FFA, 2012) but this growth has not returned European steel production to pre-recession levels and the outlook is not robust for European producers. Installations in the EU comprised, in 2009, 41 BF/BOF and 200 EAF (Ecofys, 2009) but there have been closures since. ArcelorMittal's plant at Florange, the expected site of a CCS demonstration is now idle and ArcelorMittal have focused investments in the mining sector. The iron and steel sectors in EU countries are not expected to grow and may have to face further plant closures as older large BFs require renewal or face relocation. EU steel plants are targeting high quality, high value steels, especially for the automotive sector where they have a captive market that demands reliability. However, higher quality steels represent only a small part of the total steel market. EU steel plants are exempted from the full cost of the ETS due to the perceived risks of carbon leakage, but from 2013 allowances will be provided on the basis of benchmarks (free allowances will be provided to integrated mills that generate 1.5 tCO_2/t crude steel, whereas the benchmarks for EAF are about 0.3 tCO_2).

<u>Activities</u>: The EUR 70 million EU-funded ULCOS project is investigating CCS on BF, with a TGR process that has been tested in the Experiment Blast Furance of LKAB in Lulea, Sweden at 32 t/day and is aiming to scale up to 1 Mt/yr (0.7 $MtCO_2$/yr). However, the project's application for EU funding for the larger-scale Florange demonstration project was unable to secure funding from the various funding partners in an uncertain environment for the future of the steel plant and the price of CO_2 allowances. The project could yet be applied at a

European BF site, potentially funded via the second round of the NER300 scheme. The consortium, which contains all major EU steelmakers and research partners, is also developing pilots for HISARNA (a combination of HISMELT and partial pre-reduction with CCS that is designed for up to 1Mt/yr plants), ULCORED (CCS with DRI) and ULCOWIN/ULCOLYSIS (electrolysis).

Japan

Japan's steel industry is the world's second largest, exporting 45% of its output in 2010. It has 28 BFs and 348 EAFs, yet 80% of Japanese production is from BF/BOF (WorldSteel, 2011). Since 2001 nine ultra-large BFs have been constructed and all BFs under 2000 m^3 were shut down[16]. Production has recovered somewhat after a low in 2009 but exports have suffered due to the strong Yen. However, at the same time, internal demand for reconstruction work increased in 2011 and 2012. Japan's steel industry is modern and well-equipped to supply the Asia-Pacific region competitively with higher quality steels.

Activities: The COURSE50 programme (6 Japanese steel and engineering companies plus industry association and government) is researching the reduction of CO_2 in BF gas (alternative reducing agents such as hydrogen, coke oven gas, charcoal and electrolysis) and CO_2 capture from BFs (chemical and physical absorption of CO_2 with hydrogen-rich reducing gas). It is testing processes at pilot scale. Phase I was funded by the Japanese New Energy and Industrial Technology Development Organization (NEDO) with JPY 10 billion between 2008 and 2012. Phase II is anticipated to have JPY 15 billion. Phase I included a 30 tCO_2/day CO_2 capture plant at a Nippon Steel BF for testing chemical solvents. A steelworks is part of the Tomakomai demonstration project that aims to test CO_2 capture on a cluster of different sources and store 0.25 $MtCO_2$/yr.

Republic of Korea

At 42 Mt in 2011, Korea's output from BF/BOF has increased by 23.5% for the last two years. At 26 Mt in 2011, growth in production of EAF-produced steel settled back to 6%, similar to pre-crisis levels. POSCO dominates the Korean sector and is the world's fourth largest steel producer. The Gwangyang integrated steelworks produced 17.4Mt steel in 2008, making it the world's largest single plant. The Gwangyang site is powered by an LNG combined cycle power plant and the FINEX plant at Pohang is also powered by LNG. These sites also operate CHP plants that run on off-gases (coke oven gas, BF gas, BOF gas) from the steelworks.

Activities: POSCO CO_2 Breakthrough Framework (involving POSCO and government funders) is investigating CO_2 capture using ammonia solution absorption and waste heat utilisation. A pilot plant with a processing capacity of 50 Nm^3/hr began operation in 2008 and has achieved a capture rate of >90% and CO_2 purity of >95%. A second pilot plant of around 3.5 $ktCO_2$/yr was completed in 2011. POSCO is also developing CCS applied to the FINEX process, as well as FINEX with hydrogen-rich syngas and pre-reduction.

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[16] Approximately 1 kt/yr hot metal can be produced per 1000 m^3.

Mexico

Mexico's steel production was split between BF/BOF (26%), DRI/EAF (32%) and scrap/EAF (42%) in 2006. The proportion of DRI is expected to increase in coming years at the expense of BF/BOF.

Activities: There are no ongoing CCS activities or projects in the Mexican iron and steel sector.

Norway

Norway has a low level of iron and steel production. The 0.6 Mt of steel produced in 2011 were produced by scrap/EAF with electricity from hydro power. Consequently the emissions from Norwegian steel production are very low.

Activities: There are no ongoing CCS activities or projects in the Norwegian iron and steel sector.

South Africa

South Africa is the largest steel producer in Africa, producing 7.5 Mt of crude steel in 2011, 48% of the total African production. 53% of South African steel is produced by BF/BOF and the EAF operations have a relatively high level of indirect emissions due to coal-fired power generation. Crude steel output grew to 9.7 Mt by 2006 but has since slipped and levelled off almost 25% lower. Exports of semi-finished and finished steel products are currently 50% below 2003 levels while exports of iron ore are double the 2003 level and have increased sharply since 2007. Imports of ferrous scrap have declined to 25% of their 2003 level, while exports of ferrous scrap have increased fourfold during the same period to give a net export balance of 1.4 Mt.

Activities: There are no ongoing CCS activities or projects in the South African iron and steel sector.

UAE

Production in the UAE is around 2 Mt crude steel, but is set to increase to 3 Mt in 2012 with the addition of additional DRI/EAF capacity. The DRI process is operated with natural gas.

Activities: Emirates Steel Industries is involved in a project to capture CO_2 at their DRI plant. If successful, the project would involve capture and compression of the CO_2 by Masdar, who would transport it to ADNOC who could replace the hydrocarbon gases currently used for EOR The project will proceed if the funding can be secured in accordance with ADNOC's field development schedule.

United States

The landscape of the United States steel industry has been changed over the past decade due to bankruptcies that have left less than half the number of producers as there were a decade ago. Crude steel production, however, has recovered from a 40% drop in production between 2007 and 2009 to approach pre-crisis levels. BF/BOF production share has declined from 60% in 1995 to 38% in 2011 and consequently the industry aggregate direct CO_2 emissions per tonne of steel were reduced by approximately 33% since 1990. There are over 100 EAF facilities compared to 21 BF/BOF sites (AISI, 2011). Despite a capacity utilisation average of 74% the United States is a net importer of steel. The bright spot for the United States sector is the bullish outlook for oil and gas exploration and production. Shale gas drilling has created a resurgent market for steel in the United States to make up for a lack of construction-sector demand. In addition, lower gas prices indicate that any new steel production capacity in the United States is likely to be based on DRI.

Activities: The American Iron and Steel Institute (AISI) has a CO_2 Breakthrough programme that does not look at CCS. The programme is looking at molten oxide electrolysis and hydrogen flash smelting at lab scale. The sequestration projects that the programme is considering include using steel slags to chemically bind CO_2 and other approaches to manufacturing co-products using CO_2. AISI has identified technologies that could be transferred from the power sector to the steel sector for CCS but has no project plans.

In addition to these activities in CCUS AG countries, the World Steel Association has a CO_2 Breakthrough Programme that is focused on information exchange between the programmes in Europe, Japan, Korea and the United States and also programmes in Brazil, China.

Summary

The iron and steel sector is under considerable economic and environmental pressure resulting from the ongoing economic crisis, overcapacity in some regions, uncompetitive production in others and an anticipated tightening of greenhouse gas mitigation policies. Nevertheless, current and predicted levels of CO_2 emissions from iron and steel manufacture in almost all CCUS AG countries are incompatible with climate change mitigation unless CCS is applied. This is largely because of the dominance of coal use in the sector as a reducing agent and a fuel, but also because the process emissions cannot be avoided using any technology that is commercially available today. The exception is scrap/EAF, which, despite high recycling rates, does not have the potential to satisfy the global market.

Technically, CCS can be applied to the BF/BOF process, which has been the dominant process for the last half century. The CO_2 capture method would be very similar to those methods developed for direct flue gas capture in other sectors. Although there is little variation in blast furnace composition globally, the flue is different to a power plant so CO_2 capture must be tested and tailored and techniques such as TGR must now be optimised at scale. CCS applied to BF and coke oven gases could reduce CO_2 emissions from steel production by 50%. However, these are not the only source of CO_2 at an integrated steel mill. CO_2 capture could theoretically be applied to BOF gases and power and steam production if an economic method could be found for centralising the capture and transport of CO_2 from multiple sources. Whether or not a plant will be selected for CCS will relate to its proximity to a suitable CO_2 storage site (and other local industrial CO_2 capture projects), its technical configuration and the size of the resulting CO_2 stream from the easier-to-capture sources onsite.

The resulting overall emissions intensity of production would approach that achievable from the application of CCS to HISARNA or FINEX processes, or the application of CCS to DRI/EAF. These processes could achieve a sufficient level of demonstration for commercial investment by the mid-2020s. This is especially the case if, as expected, new steel production capacity in the United States and EU is natural gas-based DRI rather than BF/BOF.

Current estimates are that CCS could add 10-20% to steel production operating costs. If mandated by regulation or CO_2 price in one region, this could threaten production in CCUS countries as production could be relocated unless policies were able to protect high cost local producers from global competition. Europe and Australia are examples of regions that do not expect to construct significant amounts of new steelmaking capacity in the coming decades but could foreseeably close capacity. Furthermore, CCS is a highly capital intense abatement technology and investors will require assurances that policy frameworks will remain in place for several decades and that CO_2 storage solutions will remain available at economic prices. Approaches to the deployment of GHG mitigation programmes for the iron and steel sector will need to be sensitive to these issues if they are to deliver deep cuts in emissions. However, given the long lead times for technology development, the demonstration of CCS for avoiding direct (process and combustion) emissions from all the main production routes in the iron and steel sector should be prioritised globally in the next 15 years as all could have significant market share in 2030. This timetable needs to fit with an industry that has a very slow turnover of stock but which invests regularly in each production site to stay operational and competitive.

5. Refining

Refineries generally provide for their energy requirements by burning gaseous and liquid components of the oil being refined. Process emissions arise from the production of hydrogen and the operation of Fluid Catalytic Crackers (FCC). Global emissions from refineries reached 0.7 $GtCO_2$ in 2009 (IEA, 2012) from the processing of 3.7 Gtoe of crude oil. There is potential to further improve this emissions intensity, but much of the improvement could be undone by the additional processing required to meet increasing demand for desirable low-sulphur middle distillate products from potentially heavier feedstocks. In addition, as governments push for lower well-to-wheels emissions from petroleum use, the impact of additional energy inputs in demanding oil extraction environments – such as deep offshore or arctic locations – could require that balancing measures be taken at refinery sites to keep overall emissions low. Overall, CO_2 emissions from refining could increase by 30% by 2050 under current policies (Figure 12).

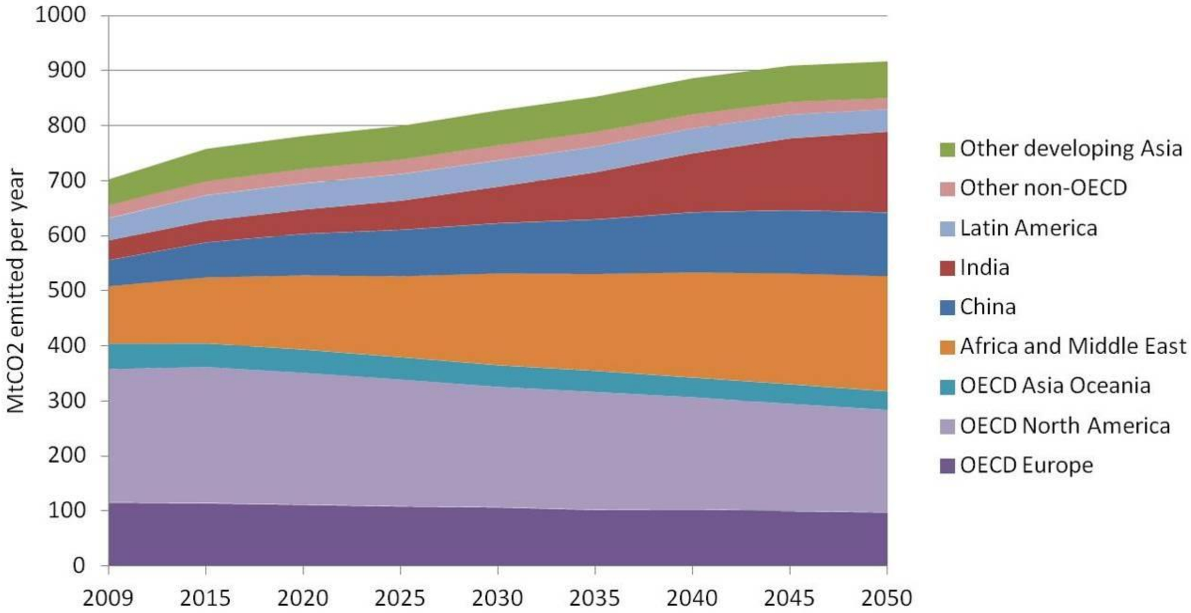
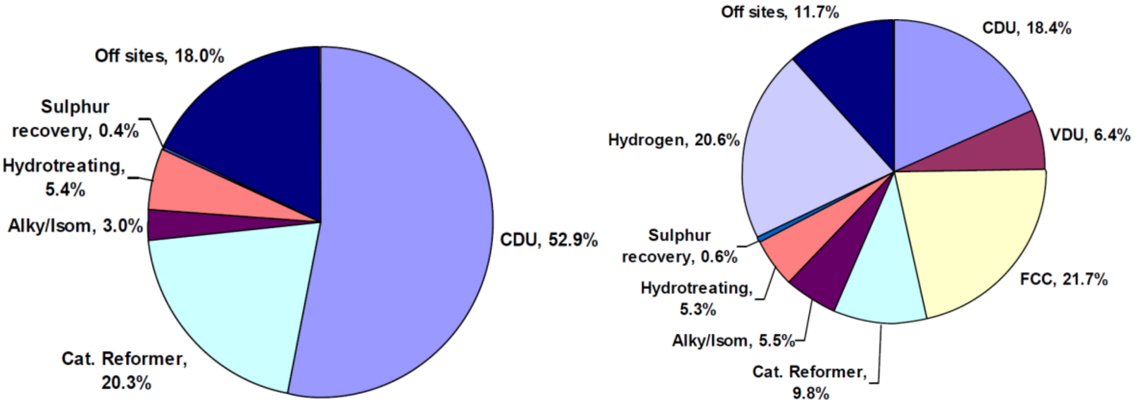


Figure 12. One scenario for regional CO_2 emissions from refining under current policies (IEA ETP 2012 4DS data)

Because refineries in different locations process different crude supplies and target different end product markets, they can be highly dissimilar and complex. Among ’conventional’ refineries, two main types can be identified: hydroskimming and conversion. A hydroskimming refinery results in a product slate after distillation that is close in composition to the crude input but does not fulfil the to market demand for transport fuels. A conversion refinery has additional processes to change the product slate, for example to raise the amount of diesel or gasoline produced, and satisfy market demand (Figure 13). In addition, coal-to-liquids and oil sands upgrading are included within the scope of this work, although CO_2 emissions from these operations are currently only a small but increasing part of global emissions from refining. Despite their differences, refineries generally operate a number of common operations that together contribute to significant site-wide emissions. These are: FCC, hydrogen production and boilers for the generation of process heat. Individually each has emissions of 0.4 $MtCO_2$/yr or more, and together they account for around 40-50% of emissions from a complex conversion refinery (van Straelen, 2010).



Hydroskimming 150 kbbl/yr refinery (0.6 MtCO2/yr) **Conversion 150 kbbl/yr refinery (1.4 MtCO2/yr)**

Figure 13. Refinery CO_2 emissions breakdowns by process for hydroskimming and conversion refineries, on a mass basis (CONCAWE, 2011)

Technology summary: Hydrogen production	
In brief	Hydrogen is an essential component of the chemical processes used to convert heavier fractions of oil into lighter fractions and reduce sulphur content, processes that are in increasing demand, even on older sites. Most hydrogen is produced by steam methane reforming (SMR) from natural gas. Gasification of residues is another route to hydrogen production. In both cases, purifying hydrogen involves removal of CO_2. These processes require large amounts of heat input. Many hydrogen facilities provide or sell carbon monoxide, syngas or steam as by-products, which means that using eat and shifting to higher CO_2 output and lower carbon monoxide output could negatively affect the economics of the plant based on by-product integration.
New technologies	Much R&D effort is being put into commercial production of hydrogen from renewably-derived electrolysis of water. Although this technology would negate the need for CCS it remains unlikely to be commercialised until the 2nd half of the century and, if it were, the refining industry would be unlikely to be an early adopter.
Trends and regional differences	Refineries in the Middle East, South America and Canada process the most medium-to-heavy crude and thus require proportionally more hydrogen for the necessary conversion processes. Several refineries in Europe are also configured to process heavier crudes.
CO_2 partial pressures/ concentrations	Separation of hydrogen from CO_2 from an SMR gas is today commonly achieved by pressure swing adsorption (PSA), which is replacing less energy-efficient amine-based hydrogen purification. If amine absorption is used, the CO_2 stream is usually 95-99% pure without any need for further treatment except drying and compression. If PSA is used, however, the CO_2 concentration can be as low as 44% and due to energy-containing carbon monoxide and hydrogen 'impurities' the gas is generally recycled to the furnace (Collodi, 2009). Despite this, the CO_2 could technically be separated by liquefaction in an intermediate step, yielding CO_2 at a pressure that would not require compression. This is the approach taken at the Porvoo refinery in Finland, from where the 0.4 $MtCO_2$/yr is sold to a range of customers in the region. Alternatively, CO_2 removal using a combination of chemical solvent and PSA could be used to purify the hydrogen stream. The Valero refinery project in Texas plans to separate the CO_2 at high purity using VSA and then purify the remaining hydrogen using PSA (Baade et al., 2012).
Applicability of CCS	Applying CCS at refinery SMR plants today could be achieved by amine solvent separation or adding an additional CO_2 separation step to the PSA process (DNV, 2010). The amine solvent regeneration step would add costs in the former case, and the intermediate separation step would add costs in the latter case (despite potentially reducing compression costs). Neither of these approaches would capture CO_2 from the flue gases of the reformer furnace. As a result, if high rates of CO_2 capture were required, partial oxidation approaches could be preferred to SMR as all CO_2 emissions could be captured together,
Likely requirement	Low

for additional heat	
Capture potential	99% reduction of emissions from hydrogen production is possible.
Size of CO_2 source	A large SMR produces between 0.7 and 1.1 $MtCO_2$/yr. Smaller SMRs (and, indeed, larger ones) could combine their CO_2 streams with CO_2 from other sources on integrated sites to improve the economics of CCS at refinery and larger industrial sites.

Technology summary: FCC	
In brief	Heavier parts of crude oil are vaporised at high temperature and a catalyst is used to break (or ‘crack’) the long-chain molecules into shorter molecules suitable for transport fuels. This helps to correct the imbalance between the market demand, especially for gasoline, and the excess of heavy, high boiling range products in crude oil. Process emissions result from burning the carbon (or ‘coke’) deposited on the catalyst to provide energy for the cracking reactions and regenerate the catalyst.
New technologies	FCCs have been in operation since the 1940s. In addition to the development of better energy management techniques, processes now exist that perform similar upgrading tasks to the FCC but with different product yields. These include hydrocracking, which is directed towards producing middle distillate transport fuels such as diesel and kerosene/jet fuel. However, these processes generally require hydrogen, which produces CO_2 and operate at much higher pressure.
Trends and regional differences	It is expected that FCC and similar processes will be installed at refinery locations in regions that will expand gasoline and petrochemical production (especially propylene) and where future supply of gasoline cannot be matched by existing refining capacity and/or crude composition. These include Africa, the Middle East and Asia.
CO_2 partial pressures/ concentrations	CO_2 is present in the flue gas at concentrations of between 7 and 13% due to the combustion of high-carbon coke and the recycle of carbon monoxide to provide heat to the process (IEA, 2012a; van Straelen, 2010).
Applicability of CCS	Applying CCS to FCC requires the use of flue gas scrubbing techniques such as the use of absorption solvents. The concentration of CO_2 in the flue gas is similar to power plants and therefore a good candidate for transfer of technological learning from the power sector.
Likely requirement for additional heat	Additional heat would be required for solvent regeneration in the flue gas scrubbing process, potentially requiring a new or larger CHP plant if sufficient excess heat were not available on site. Electricity from the CHP could be sold over the fence or to the grid but this would only partly compensate for the cost.
Capture potential	90% (~88% avoided) from the FCC
Size of CO_2 source	A typical FCC for a 450 kbbl/day world scale refinery produces approximately 0.4 $MtCO_2$/yr. Since, capture costs increase sharply below 500 kt/yr from a single source (an FCC project might be similar in scale to a 100 MW power project), this could mean that many FCC

	units are unsuitable for economic CO_2 capture unless CO_2 sources on the site, or from neighbouring sites, could be combined before storage (van Straelen, 2010).

Technology summary: Process heaters	
In brief	Process heaters collectively represent the largest category of emitters on a complex refinery (CONCAWE, 2011). A site may have 20 to 30 process heaters ranging from 2 to 250 MW spread over the site. A site with petrochemicals may have more than this. These heaters usually combust refinery residues or natural gas to provide the heating needs of specific refinery processes. It is not unusual for several of these emissions sources to be connected and emitted via a single stack.
New technologies	Modern refineries achieve higher fuel efficiencies by using natural gas CHP plants to provide onsite heat and power. In some jurisdictions biomass CHP plants are also of interest due to renewable power subsidies. Such changes could reduce the opportunities for CCS in the near- and medium-term.
Trends and regional differences	Newer refineries that are bigger, more likely to combine flue gas stacks and undertake multiple conversion processes are mostly located in Asia, especially China. Some refiners may opt to undertake emissions reductions through the use of sustainable biomass to provide heat and power on site if it is available. This would reduce the amount of fossil-derived CO_2 generated and could thus affect the economics of CCS.
CO_2 partial pressures/ concentrations	Approximately 4% from gas-fired heating or CHP units and 10% to 15% for some combined stacks (van Straelen, 2010).
Applicability of CCS	Like FCC, applying CCS to process heater emissions at a refinery site would entail flue gas scrubbing techniques. Where process heater emissions are grouped together in a single stack, or where this would be possible, particularly where it increased CO_2 concentration, CO_2 capture could be attractive and could lead to avoidance of around 80% of the emissions at a hydroskimming refinery or 70% to 75% of the emissions at a conversion refinery (Johansson *et al.*, 2013). For retrofits it could be challenging to find the space for the capture unit or the ductwork to collect emissions.
Likely requirement for additional heat	High. Steam from onsite electric turbines is often already used for heat production (in CHP), it may be necessary to construct additional process heat capacity for the CO_2 capture plant. Capture from flue gas streams with low partial pressures of CO_2 requires more heat per tCO_2 captured. The lowest cost strategy can be realised if sufficient excess heat from streams that are not already integrated into plant operation (or are currently sold off site, e.g. for district heating or agri-/aquaculture) are employed for capture solvent regeneration and complemented with a heat pump to achieve sufficient energy provision if necessary (Johansson *et al.*, 2013). Although many integrated conversion refineries would find it challenging to locate sufficient

	excess heat, this should be the first option to be explored for CO_2 capture at refinery sites.
Capture potential	90% (~88% avoided) from the stacks to which capture were applied. Sites with a small number of combinable CO_2 sources would be likely to capture up to 90% of all CO_2 from process heaters, especially if sufficient excess heat were available on site, in order to benefit from economies of scale.
Size of CO_2 source	1 $MtCO_2$/yr or more from grouped heater emissions could be possible at a refinery of 250 kbbl/day or greater, but levels of 0.5 MtCO2/yr could not realistically be achieved at refineries of 100 kbbl/day or smaller (van Straelen, 2010; CONCAWE, 2011)

CEM CCUS AG country relevance

Australia

Australia’s total operational capacity is 750 kbbl/day at seven major refineries ranging from 80 to 140 kbbl/day. Australia's refineries were mainly constructed in the 1950s and 1960s but have been extensively modified and upgraded (RET, 2012). In 2011 the closure of the 85 kbbl/day Clyde refinery was announced and in 2012 the closure of the 131 kbbl/day Kurnell refinery was announced. The five remaining refineries are conversion refineries with FCC units, which are able to process heavy crudes. Australian crude oil production is in decline and is equivalent to 80% of refinery inputs; some refineries are reliant on imports for up to 80% of inputs. Australian refineries do not meet inland motor fuels demand (20% of gasoline and diesel is imported) and diesel production capacity is being increased at Lytton refinery. Australia’s refineries are not large in global terms but could capture 1 $MtCO_2$/yr if 50% of the refinery emissions were suitable for CCS.

Activities: There are no ongoing CCS activities or projects in the Australian refining sector.

Canada

Canada has 15 full refineries that manufacture a range of petroleum products. Total Canadian refining capacity is 1,900 kbbl/day. 10 refineries currently have capacity of over 100 kbbl/day. Aproximately 23% of Canadian refinery production was exported in 2011, while two-thirds of produced crude oil was exported (Statistics Canada, 2012), mostly to the United States Additionally, there are seven oil sands upgraders with a total capacity of 1,300 kbbl/day capacity that contain hydrogen facilities but not complex processing plants.

Activities: Shell’s Quest project plans to capture and store more than 1 $MtCO_2$/yr from hydrogen production, representing 25% of the emissions from an upgrader site, 80 km away in a saline aquifer formation. The project took a positive FID decision in September 2012 and aims to be operational in 2015. Enhance Energy’s Alberta Carbon Trunk Line project plans to capture 1.2 $MtCO_2$/yr from hydrogen production at a North West Redwater Partnership oil sands upgrader that has sanctioned construction to start in spring 2013.

China

Chinese refining capacity is approximately 11,500 kbbl/day and is the second largest in the world after the United States China has three refineries over 400 kbbl/day and numerous world-scale refineries of over 100 kbbl/day. It is adding capacity at a rate of approximately

750 kbbl/day/yr to meet forecast motor fuel demand growth of 5.5%/yr and a rapidly growing demand for petrochemical feedstocks. New refining capacity is also targeted to reduce the imbalance between the geographical distributions of demand and supply. Crude oil imports provide 50% of China's refinery demand. Chinese refining capacity is oriented towards distillation, FCC and coking to manage heavy feedstocks. This composition makes large Chinese refineries good candidates for CO_2 capture. In addition, China is also considering coal-to-liquids (CTL) capacity, which uses processes similar to hydrogen production from coal and leads to a relatively pure CO_2 stream that is highly suitable for CO_2 capture at the scales of Chinese plants. CTL is an energy-intense method of producing liquid fuels and CCS could reduce well-to-tank emissions to levels within proposed emissions standards in the EU and United States Although CTL has proved profitable in Inner Mongolia its expansion depends on whether concerns about water use and emissions can be overcome.

Activities: Shenhua is operating a CO_2 capture project at its CTL plant. It currently captures 0.1 $MtCO_2$/yr and is testing CO_2 storage in a saline aquifer, but plans to scale this up to 10 $MtCO_2$/yr. The project is currently on hold pending a decision on future CTL investments.

France

Ten refineries operate a total capacity of 1,500 kbbl/day, the largest of which is 350 kbbl/day and eight of which are 100 kbbl/day or more (UFIP, 2012). Almost all refined crude in France is imported from a variety of countries. Over EUR 5 billion was invested in French refineries between 2000 and 2009 to improve environmental performance, safety and efficiency. No new refineries have been commissioned since 1967 but additional processing units have been added to increase the output of gasoline and diesel and reduce fuel oil output. Inland diesel demand continues to increase, leading to a necessity for diesel imports at the expense of gasoline exports. The French refining industry has raised concerns that the refining margin (difference between crude price and refined products prices) in Europe today is insufficient to cover refinery costs, and as CO_2 costs are expected to rise substantially in Europe, further refinery closures in France could be envisaged following the closure of one large refinery and other smaller refineries in recent years.

Activities: Two refineries fall within the scope of the Le Havre CCS cluster project, but this project remains at the conceptual stage and attention is focused on the development of a pilot facility at a power plant in the port area. Refinery hydrogen production is, however, viewed as a possible CCS demonstration project in France.

Germany

Germany's refining capacity stands at approximately 2,000 kbbl/day and serves Europe's largest national demand for vehicle fuels. Ten of its twelve operational refineries are 100 kbbl/day or greater, with the largest at 285 kbbl/day. The 300 kbbl/day Wilhelmshaven refinery, which did not contain sophisticated conversion equipment has been closed since 2009. German refiners face many of the same challenges as their counterparts in France and the UK as regulations, crude oil prices and new capacity overseas squeezes margins.

Activities: There are no ongoing CCS activities or projects in the German refining sector. North Rhine Westphalia has considered the role that CCS might play in its heavily industrial region. The Rotterdam CCS Initiative has provision in its long-term planning for the possibility of inland shipping of CO_2 to Rotterdam along the Rhine for offshore storage North Sea.

Japan

Japan is the world's 3rd largest oil consumer and has 4,700 kbbl/day of refining capacity spread across thirty facilities (EIA, 2012). In recent years, the sector has been characterized by overcapacity as demand for residential oil and motor fuels have reduced due to high prices and biofuel standards. This led to refinery closures of 560 kbbl/day between 2000 and 2010. Further closures of 600 kbbl/day up to 2015 are foreseen as export opportunities decrease due to new capacity in emerging Asian economies. Further efficiencies are also sought in the sector and investments in additional cracker capacity are scheduled to enhance competitiveness but could lead to the closure of an additional 800kbbl/day. Due to the March 2011 earthquake, imports have increased to cover refinery shutdowns and fuel oil consumption has increased to provide power supplies. Most capacity is not yet back online.

Activities: In March 2012, the Japanese government confirmed the next phase of the Tomakomai demonstration project, which will test CO_2 capture from a cluster of different sources near to the offshore geological storage site being characterised. The cluster includes a refinery from which 0.1-0.2 $MtCO_2$/yr are scheduled to be captured from hydrogen production at the refinery from 2015 to be stored offshore in a saline formation.

Republic of Korea

The Republic of Korea has no proven domestic oil reserves yet is home to three of the 10 largest crude oil refineries in the world. Total imports rose approximately 6% between 2000 and 2010, with 75% coming from the Middle East in 2010. Total refining capacity at 6 sites is 2, 700 kbbl/day, with individual capacities of the five largest rated at 817, 750, 565, 310 and 270 kbbl/day (EIA, 2012a). Although over than half of the refinery output is consumed by industry, especially petrochemicals, Korean refineries are producing lighter products following recent upgrades. In 2009, 45% of the gasoline and diesel output was exported and the country is likely to remain a major exporter in the region.

Activities: There are no ongoing CCS activities or projects in the refining sector in the Republic of Korea.

Mexico

Although Mexico exports approximately half of its crude oil production, mostly to the United States., it has refinery capacity of 1,500 kbbl/day, all owned by Pemex. The largest refinery is 330 kbbl/day and a new USD 10 billion 300 kbbl/day facility is under construction. Other refineries, such as Minatitlan, have been expanded in recent years to increase gasoline and diesel output. Most of Mexico's crude oil is a heavy sour variety. In general, the heavier crudes are exported to the United States, which has more sophisticated processing capabilities, whereas Mexico's lighter crudes are retained for domestic refining. Mexican oil production is declining by 0.6%/yr and Mexico has been forecast to become a net importer by 2020, to the tune of 1,000 kbbl/day by 2035 (EIA, 2011). The origin of these imports could affect refinery emissions, most probably leading to an increase in refinery CO_2. Scheduled refinery upgrades already indicate this trend as they move towards a reduction in fuel oil output and an increase in gasoline, which requires additional conversion processes.

Activities: There are no ongoing CCS activities or projects in the refining sector in Mexico.

Norway

Norway's two refineries have a total capacity of approximately 319 kbbl/day, and both are over 100 kbbl/day (116 and 203 kkbbl/day). Most of their production is exported. The refineries are configured to process predominantly Norwegian crude, which is relatively light and sweet oil but which does require conversion to meet the demand for diesel and gasoline. Almost all naphtha and fuel oil is exported and almost 90% of Norway's crude oil is exported rather than refined in Norway.

Activities: The Technology Centre Mongstad (TCM) project is testing CO_2 capture on 11% of the emissions from a refinery cracker at Norway's largest refinery. TCM is testing amine and chilled ammonia solvents and will capture 74-82 ktCO_2/yr. Scale-up is planned for around 2018.

South Africa

South Africa meets 95% of its oil demand through imports, most of which is crude oil imported for processing at 4 refineries. Total refining capacity is 703 kbbl/day, which includes 508 kbbl/day of crude oil refining capacity (which increased 11% between 1997 and 2007) and 195 kbbl/day of CTL refining capacity (SAPIA, 2012). There has been an upwards trend in the ratio of gasoline/diesel demand that has led to a shortfall in gasoline production from refineries in 2011. A new 400 kbbl/day refinery project is under consideration to meet rapidly growing product demand and limit imports. If the project goes ahead it will raise emissions from South Africa's refining sector, which already has high emissions of 3.2 MtCO_2/yr due to the use of CTL processes.

Activities: There are no ongoing CCS activities or projects in the refining sector in South Africa.

UAE

Currently the UAE has around 700 kbbl/day of refining capacity and is planning to expand this substantially. In 2009, 93% of crude produced was exported and the UAE hopes to reduce this percentage by moving into refining and petrochemicals. Three refineries have capacities over 100 kbbl/day, with the largest at 350 kbbl/day. An additional 300 kbbl/day refinery is proposed and is at the FEED stage. This is part of 417 kbbl/day of expansions that are on the table, plus investment in 'bottom of the barrel' crackers to increase product output. Although Dubai crude is a light oil, it seems likely that emissions will increase from the UAE refining sector in coming decades due to capacity expansions, changes to the product slate for petrochemical and fuel demand, and desulphurisation of sour input.

Activities: There are no ongoing CCS activities or projects in the refining sector in UAE.

UK

The UK has 7 operating refineries with a total capacity of 1,700 kbbl/day that supply 85% of UK inland consumption of products (UKPIA, 2012). These refineries operated at 82% capacity in 20011. Six out of seven of the UK's refineries have a capacity of 200 to 300 kbbl/day (largest in country) and all refineries operate catalytic crackers and advanced processing facilities, such as alkylation plants. 80% of feedstock comes from the North Sea. The UK is a net exporter of gasoline and a net importer of diesel. At 450 MtCO_2/yr, Refineries emit around 3% of the UK's CO_2 emissions, with absolute annual emissions falling by 0.6% in 2010. Operations at the Teesside refinery were suspended in 2009 and in May 2012 it was announced that the Coryton 220 kbbl/day refinery would close.

Activities: There are no ongoing CCS activities or projects in the UK refining sector.

United States

124 refineries operate with a total capacity of 1,800 kbbl/day in the United States (CRS, 2010). However, this includes some refineries that are currently idle due to overcapacity as a result of decreasing gasoline demand and increased gasoline imports. 11 of these refineries provide a quarter of the total capacity. The largest of these has a capacity of almost 600 kbbl/day and the smallest around 300 kbbl/day. Approximately 40 refineries are over 100 kbbl/day. The United States supplies 35% of the crude oil input to United States refineries, with the largest import sources being Canada, Saudi Arabia, Mexico and Nigeria. This composition represents a significant shift towards heavier, sourer crudes and as a result United States refineries have invested in multi-million dollar conversion process upgrades. On the other hand, refineries may be affected by the projected increases in United States crude oil production (light tight oil) and decreases in gasoline demand due to efficiency and the global markets for refined products. Overall, the United States is likely to remain the largest oil refiner in coming decades notwithstanding additional plant closures to keep capacity utilisation high, No fuel standards are proposed in the United States to account for lifecycle well-to-pump emissions and the focus is on vehicle efficiency and biofuels. Therefore the trend towards conversion processes that consume more energy and emit more CO_2/t of fuel product produced does not yet pose a problem that CCS could be required to address.

Activities: There are no ongoing CCS activities or projects in the United States refining sector.

Summary

The technology and national summaries outlined above highlight that the fundamental issues for CCS in the refining sector relate to: the breakdown of emissions at complex refineries into individual processes at different scales; the growing demand for light transport fuels, requiring increasingly complex and energy-intensive refining processes; the trend towards heavier or synthetic crude oils, the development of new refinery sites, and the extent to which policymakers regulate lifecycle emissions for transport fuels. It will be the interplay between these issues that will determine the application of CCS at a given refinery. Retrofitting of CO_2 capture in the near- to medium-term is likely to be dependent on the presence of large hydrogen production facilities and CHP plants, or the ability to combine emissions sources for flue gas scrubbing and use excess heat for solvent regeneration.

In addition to the activities described for CCUS AG countries, the Green Hydrogen project based in Rotterdam in the Netherlands is a refinery CCS project in Europe. Air Liquide’s new hydrogen plant has been opened as ‘capture ready’ but was not able to secure EU funds in the first round of the NER300 to progress with storage of 550 ktCO_2/yr.

With the exception of CO_2 capture from hydrogen production – which is well-known and can be sufficiently low-cost to be commercially attractive for EOR operations in some regions – activities in the refining sector appear to be less well-developed that those in the iron and steel and cement sectors, despite the close involvement of major oil companies in the CO_2 storage aspects of CCS. Due to the diverse nature of refinery designs and their suitability for CCS it will require a focused effort to bring the sector to an improved understanding of the potential and needs for CCS to reduce emissions across a major refinery site. One starting point that could enable information to flow between firms and influence new designs could be the engagement of EPC contractors in addition to refinery operators.

6. Cement

Concrete, based mainly on Portland cement, is the most widely used material on Earth (Gartner, 2004). The production of cement was responsible for 5-6% of global CO_2 emissions from stationary sources in 2009. It directly emitted approximately 2.3 $GtCO_2$ of CO_2 in 2009 (IEA, 2012), of which around 60% were process emissions. Indirect emissions, mainly from electricity production, amounted to no more than 10%. Cement production was 3.1 Gt in 2009, following a 4% growth rate between 2007 and 2009 despite the economic crisis and on the back of a 67% increase in production between 2000 and 2007 (Mott MacDonald, 2010). Half of production is in China. Global demand could increase by around 50% between now and 2050 (IEA/WBCSD, 2009) in a high demand scenario with more than 95% of the growth in cement demand and production coming from non-OECD countries. Figure 14 shows the IEA figures for a low demand scenario in which production still grows by 30%.

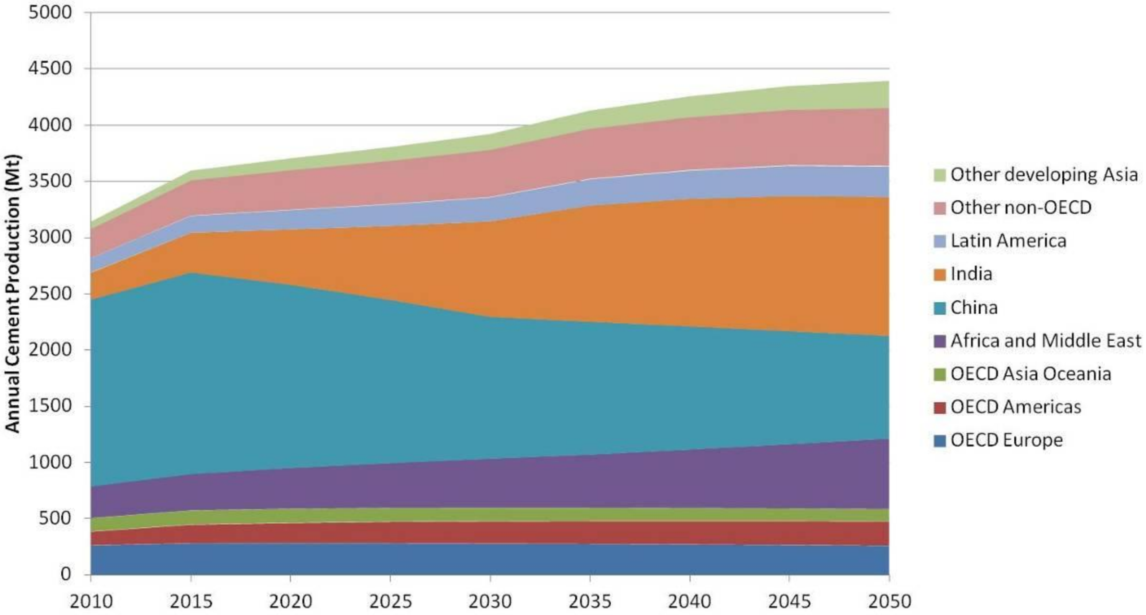


Figure 14. One scenario for the regional development of cement production (IEA ETP 2012, low demand scenarios)

The trend is towards ever-larger facilities, generally located near limestone production. In Europe cement production sites range between 0.25 Mt/yr and 1.8 Mt/yr. Some of the world's largest facilities today are in the United States (4Mt/yr) and Indonesia (5.4Mt/yr). Indocement Tunggal Prakarsa operates a multi-plant site in Indonesia with a capacity of 11.9 Mt/yr.

Cement is generally 91% clinker, ground with 4% gypsum and 5% limestone. It is the clinker production process that generates CO_2 in a cement kiln in two phases: firstly, limestone is calcinated at 850-950°C – during which CO_2 is released from the limestone – and then it is 'burned' at over 1400°C to produce clinker. Both processes commonly use coal as a fuel. The energy efficiency of clinker production improved by 30% between 1970 and 1995 and had begun to plateau before the 'dry' process using pre-calciner kilns reduced it by 20% more. The phase out of vertical shaft kilns in favour of rotary kilns worldwide is still ongoing and contributing to average efficiency improvements in China where they are still used. CO_2 capture could be applied to clinker production via two different methods. Today, the best plants achieve an efficiency of 3.1 GJ/t, but efficiency measures are not foreseen to much more closely approach the theoretical minimum of 1.6 to 1.85 GJ/t (IEA, 2009). Some plants will have the opportunity to reduce combustion emissions by using alternative fuels, and process emissions can be reduced through clinker substitution. All of these approaches have theoretical and practical limits however, and would not achieve total emissions reductions of more than around 50%, as can be concluded from IEA (2009).

Technology summary: Kiln flue gas scrubbing	
In brief	The technology would be the same as flue gas scrubbing in other sectors, i.e. use of absorption solvents such as amines to absorb up to 95% of all CO_2 leaving the kiln. Due to the relatively high concentration of CO_2 in the flue, CO_2 absorption would be more efficient than for the power sector. SO_x, NO_x and dust would need to be removed before CO_2 capture, and this would require equipment that can operate in a high dust environment. The increase in energy consumption through the application of flue gas scrubbing could be between 30% and 103% including purification and compression, depending on fuel used, solvent used and the steam source for solvent regeneration (ECRA, 2009).
New technologies	• Capture costs could be reduced by using lower sulphur raw meal. • Carbonate looping: The CO_2 is separated from the flue gas, which has been enriched with CO_2 without the need for additional oxygen from an air separation unit. CaO is used in a fluidised bed as an effective sorbent to form $CaCO_3$, which is then calcinated at 900°C to produce pure CO_2. The CaO is recycled. Over time the sorbent becomes deactivated but can be added to the clinker burning process as precalcinated feedstock. Although developed for the power sector, it could be more suited to the cement sector because most cement plants are located near lime production and cement companies are often vertically integrated into quarrying (Bosoaga, 2009). Pilot-scale tests are underway in Germany (1 MWth), Spain (1.7 MWth) and Mexico (Fennell et al., 2012).
Trends and regional differences	It has been estimated that a 3 Mt/yr plant in Asia would have half the capture costs per tCO_2 compared to a UK 1 Mt/yr plant (IEAGHG, 2008). Larger plants would have lower capture costs.
CO_2 partial pressures/ concentrations	25% (IEAGHG, 2008; Hassan, 2005)
Applicability of CCS	At large cement plants flue gas scrubbing would be technically appropriate for reducing CO_2 emissions. However, the cost of CO_2 capture, transport and storage today could lead to a doubling of the cost per tonne of cement.
Likely requirement for additional heat	It is likely that most sites would need to supply steam from a new and dedicated CHP plant, but steam could also be imported from a local power plant if available. For example, many Indian plants have captive power plants ensuring reliability of supply and these could be used to supply steam with low additional energy cost. A 1Mt/yr cement plant would be likely to require a 45 MW_e CHP (IEAGHG, 2008).

Capture potential	Approximately 90% capture, reducing CO_2 emissions by between 74 and 85% (IEAGHG, 2008; Mott MacDonald, 2010)
Size of CO_2 source	The CO_2 intensity of cement production ranges from 0.5 (state-of-the-art) to 1.2 (U.S. representative figure) tCO_2/t cement (Choate, 2003). Over 0.5 $MtCO_2$/yr could therefore be captured from an older 0.5 Mt/yr cement plant, accounting for the energy penalty of capture, and larger plants could capture larger quantities of CO_2 (IEAGHG, 2008).

Technology summary: Oxy-firing process	
In brief	Operating a kiln in an enriched oxygen environment has been shown to increase throughput. The proposed approach is to use oxy-firing only in the pre-calcination step that would result in a nearly pure CO_2 stream from the calcination process. However, it would need to operate as a ‘separate line’ calciner, which could cause operational problems. Oxy-firing requires a relatively capital-intense ASU to supply the oxygen but this occupies a (up to 8 times) smaller space on site than the equivalent footprint of the CO_2 absorbers for flue gas scrubbing. Energy consumption would be increased by 13% (IEAGHG, 2008), mostly due to a doubling of the electricity requirement to supply the ASU and CO_2 compressor. The impact of oxy-firing on cement quality is not fully understood and this, along with the technology risk of kiln redesign to accommodate an undemonstrated technology, presents a challenge to the adoption of this route.
New technologies	• The next step after partial oxy-firing would be to apply oxy-firing to the entire cement plant (calcination and clinker burning). Whilst technically feasible, this would require significant re-design to accommodate the increased temperatures and recirculation of CO_2 into the kiln. • Fundamental research is required in a number of areas to be able to apply oxy-firing to the full plant: how do heat transfer characteristics and chemical kinetics change? how might elevated temperatures affect the kiln wall?; what’s the optimal ratio of O_2 to recycled CO_2?; how can the raw mill, preheater and kiln be made airtight? how can cycles of volatile compounds be controlled? These changes in design could make retrofitting of oxy-firing very unlikely, although rebuild of the pre-calciner alone may be more attractive than flue gas scrubbing (IEAGHG, 2008).
Trends and regional differences	Most regions now operate large, integrated cement plants using the ‘dry’ process, which incorporates a pre-calciner that could be converted to (or replaced by) oxy-firing.
CO_2 partial pressures/ concentrations	90%
Applicability of CCS	Oxy-firing appears particularly suitable for cement plants due to the relatively small proportion of combustion emissions compared to process emissions, which reduces the amount oxygen needed per tCO_2 captured overall, and thus costs. For comparison, flue gas scrubbing

	costs increase more strongly in relation to the amount of CO_2 captured. One study estimates oxy-firing CCS costs to be half of flue gas scrubbing costs per tCO_2 captured on the basis of desktop calculations that await technical validation (IEAGHG, 2008).
Likely requirement for additional heat	The main concern is the additional energy required for the ASU.
Capture potential	Capture of 90% from the pre-calciner could avoid site-side emissions by 61%. Applying oxy-firing to the pre-calciner and kiln could avoid 92% of emissions.
Size of CO_2 source	A 1 Mt/yr cement plant would capture approximately 0.47 $MtCO_2$/yr (IEAGHG, 2008). This is less than flue gas scrubbing as additional boiler capacity is not necessary.

CEM CCUS AG country relevance

Australia

Australian cement production in 2009 was 9.2 Mt, with two thirds of the energy provided by coal, coke and diesel (CIF, 2010). The use of pre-calciners in the dry process has almost entirely displaced other forms of cement production in Australia. The Australian cement sector participates in the WBCSD Cement Sustainability Initiative (CSI) via the Cement Industry Federation (CIF).

Activities: There are currently no projects on CCS in the Australian cement sector. Under the Greenhouse Challenge Plus program the sector has had GHG reduction targets between 1997 and 2012.

Canada

In 2008, Canada produced 15 Mt cement at fifteen plants (CAC, 2010). The Cement Association of Canada has highlighted the fact that 40% of cement production costs are energy costs.

Activities: Pond Biofuels has operated a pilot project for biological capture from the flue gas of a cement plant since 2009 at an investment cost of CAD 4 million.

China

China continues to experience unprecedented urbanisation and a year-on-year growth in construction. In 2010, cement production was 1,870 Mt, up 15.5% compared to 2009. This growth rate has probably not been sustained in 2011 due to a macroeconomic downturn affecting the construction sector, and exports fell by 15% in 2011, but nevertheless China's output will likely overshadow production in the rest of the world for the next two decades. To counteract declining profitability and inefficiencies of smaller older plants, an aggressive process of consolidation is ongoing. The national manufacturing company, CNBM, has set itself up to have the largest portfolio of cement production capacity by the end of 2012 (Mott MacDonald, 2010). However, between 30% and 35% of the industry is still using inefficient vertical shaft kiln technology. Some forecasts suggest that Chinese cement demand could peak by 2020 and the country would move into a period of replacing rather than growing capacity. Sinoma, a Chinese engineering company, has a 27% global market penetration for contracted new kiln capacity outside China and is the type of company that could spread new technology configurations.

Activities: There are currently no projects on CCS in the Chinese cement sector.

France, Germany, UK

In France and Germany, cement production in 2011 was 19.4 Mt and 24.8 Mt respectively, both up 8% on 2010 and nearly back to pre-crisis levels (SFIC, 2012; VDZ, 2012). 42 sites were operational in France and two-thirds of French cement exports were to the UK and Germany. 54 sites were operational in Germany, 19 of which have a capacity of over 0.5 Mt. In the UK, production in 2010 was 7.8 Mt at 10 sites in the UK (MPA, 2011). The European Cement Research Academy (ECRA) was established in 2003 and is funded by its members (companies operating cement plants, national cement associations and international cement associations). French company Polysius is one of the world's top equipment suppliers with a share of 16% of currently contracted kiln capacity (excluding China). HeidelbergCement (Germany) and Lafarge (France) are among the world's largest cement companies with 3.1% and 5.8% market shares respectively in 2008. ECRA has suggested that, despite the apparent technical feasibility of CCS on cement plants, without a political framework that effectively limits the risk of carbon leakage, CCS on cement will not occur.

Activities: ECRA has been studying CCS since 2007 and has made some significant contributions to knowledge at a laboratory scale. The next steps for this work are to test oxy-firing and flue gas scrubbing processes at pilot and then demonstration scales. The German Combustion Research Association (DVV) and the German Cement Works Association (VDZ) are studying calcium looping for clinker burning. Cembureau, the European industry association for cement manufacturers is developing a roadmap for publication in 2013 that will consider CCS.

Japan

Japanese kiln capacity peaked at 98 Mt in 1993 and has now dropped to 56 Mt. However, the number of integrated sites only dropped by 25% over the same period to 31 and a kiln operation ratio of 86% has been maintained due to closure of smaller sites. Production in 2011 was 56 Mt, 17% of which was exported and 72% of which was produced in modern kilns with pre-calciners.

Activities: A cement works is part of the Tomakomai demonstration project that aims to test CO_2 capture on a cluster of sources and store 0.25 $MtCO_2$/yr in total.

Republic of Korea

Cement production in the Republic of Korea was 52 Mt in 2011 (UN, 2012). Exports from the Korean cement sector reached a new high in 2011 of 4 Mt, an increase of 62% on 2010.

Activities: There are currently no projects on CCS in the Korean cement sector.

Mexico

Mexican company Cemex enjoyed a 3.4% global market share 2008, making it one of the world's largest cement companies. National production was 10 Mt in 2010 (UN, 2012).

Activities: There are currently no projects on CCS in the Mexican cement sector.

Norway

HeidelbergCement has two production sites in Norway and CCS has been proposed at the NORCEM plant in Brevik.

Activities: An EUR 1.7 million study is being carried out with a view to commissioning a pilot facility by 2018.

South Africa

South African cement sales amounted to 11 Mt in 2011 and have been relatively stable over the last four years.

Activities: There are currently no projects on CCS in the South African cement sector.

UAE

The UAE is a major supplier of cement in the region and has enjoyed a construction boom in recent years. However, under increased competition and slowdown in housing markets, it faces a period of restructuring.

Activities: There are currently no projects on CCS in the cement sector in UAE.

United States

After China and India, the United States is the world's third largest cement producer, producing around 68 Mt in 2011 (van Oss, 2012). According to Portland Cement Association (PCA) estimates, United States cement plants achieved an average capacity utilisation rate of 82% in 2008 but did not satisfy total United States demand, for which 11 Mt was imported from China, Canada, Columbia, Mexico, and the Republic of Korea.

Activities: Cemex USA was awarded USD 1.1 million from the Department of Energy in March 2010 to demonstrate a 1 MtCO_2/yr dry sorbent CO_2 capture technology at one of its cement plants (Mott MacDonald, 2010). However, the project was later abandoned. Skyonic was awarded USD 25 million from the Department of Energy in July 2010 for a 75 ktCO_2/yr CO_2 capture and mineralisation project at Capitol Cement Plant in San Antonio. The plant is currently under construction for operation in 2014. The technology is designed for low concentrations of CO_2 in flue gases, as opposed to oxy-firing. Whilst it is not a CO_2 storage project it could provide useful information about the capture of CO_2 in the sector.

Summary

Cement is not as widely traded as steel but international trade exists and the high costs associated with CCS could seriously disadvantage a site's competitive position vis-à-vis sites without CCS. As noted above, flue gas scrubbing would have to process approximately one tonne of CO_2 for every tonne of cement produced, which could not only require the capital and operational costs of raising steam for solvent regeneration, but could double the cost of cement production. Oxy-firing, on the other hand, would require some redesign of the plant but is expected to add on only about 25% to the production costs for a 60% reduction in emissions. Over 90% reduction through oxy-firing could be possible at a later stage. Despite the promising studies of oxy-firing for cement production with CCS, however, the technology still requires demonstration and thus presents a technology risk compared to flue gas scrubbing that needs to be overcome before commercial investment and thus cost optimisation could be expected. In a world without a climate policy regime that could realistically enforce the use of CCS at these cost levels, the near-term focus must be on fundamental research to prove the oxy-firing concept, exploration of heat integration opportunities for both systems and reducing costs through learning-by-doing.

In contrast to other sectors, cement manufacturing benefits from a relative homogeneity of technologies and production sites. Furthermore, technology developments in the sector are driven by a relatively small number of equipment suppliers who supply the various cement production companies worldwide (Mott MacDonald, 2010). This has the potential to simplify the process of demonstrating the technology options for CO_2 capture and subsequently deploying these technologies where it becomes economic to do so. ECRA's projection of between ten and twethy projects each storing 2 $MtCO_2$/yr constructed by 2030 globally seems achievable if rapid and collaborative progress is made in the coming decade. However, the application of CCS to all new plants over 2 Mt output/yr by 2030 (IEA and WBCSD, 2009) will be an extremely challenging goal without rapid technological improvement and targeted climate policy.

In addition to economic considerations, before investments proceed in commercial CCS projects in the cement sector, companies will need to become comfortable with changing an established and reliable process. The nature of the industry is to focus on incremental improvements to the final product and a high level of quality assurance for a conservative customer base. Cement producers today are often vertically integrated and self-sufficient, whereas flue gas scrubbing might be most efficiently operated in cooperation with a local power plant . Furthermore, and as with iron and steel, operating the chemical processes of CO_2 capture requires a different skill set to that which is generally possessed by cement plant operators and so the technology development phase is unlikely to be managed in-house.

Given the slow turnover of stock in the sector (kilns can operate for up to fifty years) and given the apparent difficulties with retrofitting CCS (especially oxy-firing) at cement plants, consideration should be given to whether additional capacity and replacements of over 2 Mt capacity scheduled for the 2015 to 2030 period should accommodate CCS potential into their designs and locations.

7. Chemicals

Whereas energy consumption for iron and steel has been relatively stable despite production increases, chemicals and petrochemicals, which are the heaviest industrial energy users, doubled their energy and feedstock demand between 1971 and 2004 (IEA, 2007). The chemical and petrochemical sector accounts for 30% of global industrial energy use and 16% of direct CO_2 emissions. The difference between these percentages arises from the integration of almost half of the energy (petroleum) inputs into products such as plastics.

The chemical industry is highly diverse, with thousands of companies producing tens of thousands of products in quantities varying from a few kilograms to thousands of tonnes. Studies of CCS in the chemical industry to date have tended to focus on a small number of energy intense processes that generate sufficiently large streams of CO_2 that CCS appears an attractive option for their decarbonisation. Many chemical facilities are located on complex chemical sites with multiple processes and multiple emissions sources. In this sense the sector is similar to the refining sector and a number of chemical and petrochemical sites are in fact integrated with refineries. As with refineries, we focus here on the small number of processes that would lend themselves to adoption of CCS.

Technology summary: Ammonia production	
In brief	Ammonia is the source of nearly all the synthetic nitrogen fertilizers produced in the world. It is produced by combining hydrogen and nitrogen at high temperatures and pressures. Since hydrogen is produced from fossil fuels, there are two sources of emissions: process emissions from the separation of the hydrogen from the carbon in the coal or natural gas; and combustion emissions from the provision of heat. Globally, the process emissions represent approximately two-thirds of CO_2 emissions (IEA, 2007; Strait and Nagvekar, 2010). Hydrogen production for ammonia is very similar to that for refining (by steam methane reforming) or similar to CTL, and takes the same approach as pre-combustion CO_2 capture from an IGCC power plant. However, whereas crude oil refineries overwhelmingly use natural gas, 27% of ammonia production capacity is coal-based compared to 67% natural gas-based (IFA, 2009b).
New technologies	• The separation of hydrogen from CO_2 from SMR is often achieved by solvent-based condensation/refrigeration, which is energy-intensive and produces almost pure streams of hydrogen and CO_2. Pressure Swing Adsorption (PSA) is a favoured option that reduces the energy use but results in a less pure CO_2 stream and would make CO_2 capture more problematic as this tail gas is often used as a low calorific fuel onsite • Hydrogen projects based on gasification can also employ PSA, which is preceded by a Rectisol/Selexol[17] solvent-based step. • Membranes to deliver a pure CO_2 stream are under development but are still at an early research stage. • Polygeneration is also emerging as an attractive route to ammonia from coal. Gasification produces hydrogen that can be used as a power fuel or an ammonia feedstock depending on demand and market conditions. This would yield a large, pure CO_2 stream.
Trends and regional differences	97% of coal-based capacity is in China. United States plans to construct additional coal-based polygeneration plants may now be under threat due to low natural gas prices. Growth in ammonia production capacity is mostly foreseen in Asia (16%), Middle East (32%) and Africa (82%) up to 2020 due to low-cost gas (KBR, 2012).
CO_2 partial pressures/ concentrations	Process emissions captured by the solvent absorption process for separating hydrogen would require minimal clean up before compression. Process emissions captured by newer PSA processes can be purified by a subsequent liquefaction step that could remove the need for further compression (Reddy, 2009), or preceded by an amine-based CO2 stripping step. Combustion emissions would be likely to have CO_2 concentrations of between 4 and 15%, depending on fuel source. At these concentrations, it is unlikely that CO_2 capture would be proposed unless the boiler was large (providing heat to multiple end-

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[17] Trade names for processes based on methanol or the dimethyl ethers of polyethylene glycol as solvents.

	uses on site, see section on refinery process heaters) or unless a different hydrogen production route was preferred to enable capture of process and combustion emission together (such as partial oxidation) and thus achieve higher rates of CO_2 capture.
Likely requirement for additional heat	Low and mostly for CO_2 liquefaction/separation, except if combustion emissions were also targeted.
Capture potential	If 99% of process emissions were captured, emissions from ammonia production could be reduced by between 65 and 70%.
Size of CO_2 source	• A coal-based unit produces roughly 2.4 times more CO_2/t of ammonia than a natural gas-based unit (IFA, 2009a, GHD, 2009) and 3 times as much if petcoke is used (EPA, 2009). Many plants constructed in the 1970s are still operational with a capacity of around 1 kt/day ammonia, but newer plants generally have sizes of over 1.5 kt/day and the world's largest plant under construction is 3.5 kt/day and is coal-based. If process emissions at a state-of-the-art facility amount to approximately 1.2 tCO_2/t of ammonia from natural gas (EPA, 2009) then a plant producing more than 1.5 kt/day ammonia operating at a 75% capacity utilisation would generate at least 0.5 $MtCO_2$/yr. The CO_2 source would be approximately 45% larger if non-process emissions were also captured. • However, CO_2 separated from hydrogen is already used for the conversion of ammonia to urea[18]. Around 37% of the separated CO_2 is used in this way globally (i.e. gas- and coal-based processes), leaving around 60% of the process CO_2 to be vented. For ammonia production sites in the United States, the proportion of ammonia that is converted to urea ranges from 14% to 89% (EPA, 2009). Using stoichiometry, on average 42% of process CO_2 is used to generate urea in the United States. Five out of twenty four operating plants are not integrated with urea production in the United States. • If large natural gas facilities today are of the scale of 1.5 kt/day then a plant that converts 50% of its ammonia to urea will emit 0.37 $MtCO_2$/yr and a plant that converts 89% of its ammonia to urea will emit 0.03 $MtCO_2$/yr. Thus, integrated natural gas-based plants do not look like a good CCS opportunity even if non-process emissions were captured[19]. • On the other hand, a modern coal-based ammonia plant would only need to have a capacity of at least 1.2 kt/day (process emissions of 1.8 tCO_2/yr at 75% capacity utilisation) to emit over 0.5 $MtCO_2$/yr of process CO_2 after urea production. If the plant were not integrated

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[18] This utilisation of CO_2 does not prevent its later release to the atmosphere and so is not understood to be CCS across the lifecycle.

[19] Based on 0.88tCO_2 consumed per tonnes of urea produced, which means that each tonne of ammonia needs to be reacted with more than 1.3 tCO_2, assuming the stoichiometric yield is not achievable. In India steam reforming of natural gas does not satisfy the demand for CO_2 of the urea manufacturers at some sites and so CO_2 is captured from other fossil fuel flue gases, an approach that has been deemed eligible for CDM credits.

	into urea production, this capacity would be less, at 0.7 kt/day.
Applicability of CCS	CCS appears to be appropriate for ammonia plants that are less than ten years old, and are either coal-based or are not integrated into urea production.

Technology summary: Methanol production	
In brief	After ammonia, methanol provides the world's second largest demand for hydrogen, around 5 to 6 Mt hydrogen/yr is produced for manufacture of about 50 Mt methanol (Carbon Counts, 2010; Methanol Institute, 2011). As with ammonia, most hydrogen for methanol is produced via natural gas SMR, with an important initial desulphurisation step. Methanol is produced from coal in the United States and China. As with urea, the carbon content of the methanol product is sourced from the same feedstock as for the hydrogen production (i.e the gas or coal that is split up to form a synthesis gas of hydrogen and CO/CO_2). See descriptions of SMR and gasification routes to hydrogen production above.
New technologies	In addition to steam reforming and coal gasification, methanol from biomass is being developed in some regions. Biomethanol can be produced from gasification of biomass, in the same way that coal is gasified, and this leads to surplus CO_2 that is relatively pure. Any biomass can in theory be used, but current projects focus on glycerol (a by-product of biodiesel production) and wood waste.
Trends and regional differences	Methanol plants have increased in size over the past 40 years from around 0.5 Mt/yr to 5 Mt/yr. Almost all coal-based methanol production today is in China.
CO_2 partial pressures/ concentrations	• Process emissions from both natural gas- and coal-based methanol provide a relatively pure CO_2, assuming that all carbon monoxide is shifted to CO_2 in order to maximise H_2 production. • Combustion emissions from heat provision have concentrations of around 4% for natural gas and 10% to 15% for coal.
Likely requirement for additional heat	Low and mostly for compression, or liquefaction if PSA is used for CO_2 separation.
Capture potential	Applying CCS to process emissions from a large coal-fired methanol plant could avoid between 60 and 70% of CO_2 emissions.
Size of CO_2 source	• For methanol produced from natural gas, all of the carbon monoxide in the syngas produced by steam reforming is required for reaction with the hydrogen leaving approximately 0.25 to 0.5 $MtCO_2$/yr to be vented (mostly combustion emissions). • For production from coal there is a much larger supply of pure CO_2 that is not required for methanol synthesis and is normally vented. Process emissions per tonne of methanol from coal after CO_2 utilisation are approximately 1.5 to 2.3 tCO_2. World-size modern plants based on coal, however, release 5 to 10 $MtCO_2$/yr, of which two thirds are process emissions (Carbon Counts, 2010; CCRI, 2011).
Applicability of	CCS appears to be mainly applicable to coal-based methanol plants of

CCS	at least 1 Mt/yr methanol capacity in the coming decades. It is readily applicable to the process emissions, requiring only additional compression of CO_2 and, for larger plants the application of flue gas scrubbing combustion emissions appears viable also, but at greater cost.

Technology summary: Bulk High Value Chemicals (HVC) production	
In brief	The production of the building block chemicals that underpin the modern petrochemical industry are mostly derived from the lighter fractions of crude oil distillation. Processes that are CO_2 intense and also have associated process emissions include ethylene and propylene from LPG or naphtha cracking, and ethylene oxide production. Other processes, such as para-xylene production from mixed xylenes require large amounts of process heat, for which the boilers are commonly integrated into the overall chemical site steam supply. Cracker process emissions arise from the removal of carbon from the feedstock to produce shorter-chain hydrocarbons. Approximately 21 Mt of ethylene oxide are produced worldwide, mostly for conversion to ethylene glycol and then onwards to antifreeze and polymers. Global demand for ethylene oxide is forecast to grow at a rate of 5%/yr from 2009 to 2014, and around 3%/yr from 2014 to 2019 (Carbon Counts, 2010). Heat and power on large chemical sites are provided by dedicated boilers that deliver utilities site-wide, often CHP.
New technologies	Efficiency improvements are a major source of value for producers.
Trends and regional differences	The major expansions of petrochemical facilities are occurring in the Middle East and Asia, especially China and India. Middle East production is largely based on ethane and LPG, whereas Chinese production is more reliant on naphtha and, in some cases, coal. The United States is poised to continue to play a major role in the global industry, in particular if a petrochemical expansion occurs on the basis of shale gas for export. If global demand grows very strongly, European production could foreseeably grow over the coming decades but will continue to be a marginal producer cost-wise due to reliance on naphtha.
CO_2 partial pressures	• It is not possible to distinguish the process emissions in a cracker from the combustion emissions as the cracker generally uses feedstock for energy supply and has only one flue. The overall concentration of CO_2 is an estimated 13-15%. • Ethylene oxide process emissions may need to be separated from other vented gases, such as water, or may be emitted in a pure form. • Emissions from a coal-based CHP plant would be around 10-15%, whereas emissions from a gas turbine are lower, around 3-4%.
Likely requirement for additional heat	• High for cracker emissions and CHP emissions. It is likely that an integrated chemical site would need to add additional steam capacity. This could be incorporated into the design of a new site and optimised accordingly. • Low for ethylene oxide process emissions.

Capture potential	- 90% of the emissions from a cracker or CHP plant could be captured, equating to 75-88% of emissions avoided, with crackers at the higher end of the scale. - 99% of ethylene oxide process emissions might be captured, reducing overall emissions to around 60%
Size of CO_2 source	- A modern world-scale cracker has a capacity of approximately 1 to 1.5 Mt ethylene, and emissions of 1.0 tCO_2/t ethylene if based on ethane and 1.8 tCO_2/t ethylene if based on naphtha (Ren et al., 2006); if propylene is co-produced this raises allocation issues that can be resolved by assigning an 0.7 tCO_2 to each tonne of propylene. Larger plants tend to be based on ethane due to the expansion in the Middle East, and these emit around 2.5 $MtCO_2$/yr. Naphtha-based plants in the United States., Japan and Europe emit 1.4 to 1.9 $MtCO_2$/yr due to their smaller size. - CO_2 emissions from the direct oxidation of ethylene are approximately 1.16tCO_2/t ethylene oxide, of which about 45% (0.52 tCO_2) is process emissions. The world's largest ethylene oxide facilities in the United States and Europe produce almost 0.5 Mt ethylene oxide/yr. The process emissions from such a plant would amount to approximately 0.26 $MtCO_2$/yr and could be captured using physical sorbents (Carbon Counts, 2010). - CHP plants on chemical sites are rarely more than 100 to 150 MW in capacity. A 100 MW CHP plant based on coal generates approximately 0.7 $MtCO_2$. Emissions from a biomass-fired would be slightly higher but contain additional impurities. However, if a natural gas turbine were used the emissions would be in the range of 0.4 $MtCO_2$/yr.
Applicability of CCS	Among these options, world-scale ethane-, LPG- and naphtha-based ethylene crackers appear to offer the most potential for CCS but CO_2 capture would require additional heat onsite for solvent regeneration. Ethylene oxide plants appear to be too small for CCS to be a suitable proposition, unless the captured CO_2 could be combined with other local sources, in particular high purity sources such as hydrogen production. Due to the relative purity of the CO_2 stream from ethylene oxide, and the common location of plants near to petroleum producing regions (i.e. potential CO_2 storage), ethylene oxide remains of interest if combined with other sources before injection. Coal-based CHP plants offer similar prospects to ethylene crackers, but are smaller in size.

<u>CEM CCUS AG country relevance</u>

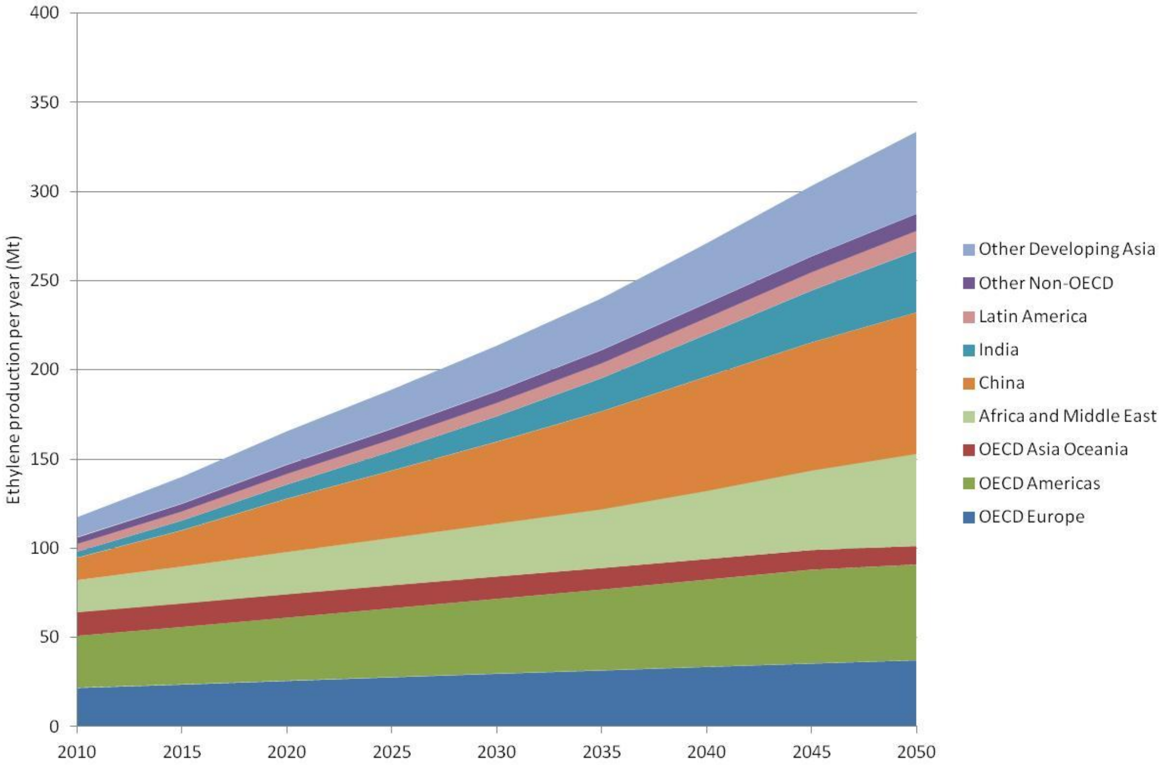

Figure 15. One scenario for the regional shares of ethylene production to 2050 (IEA ETP 2012 2DS low demand)

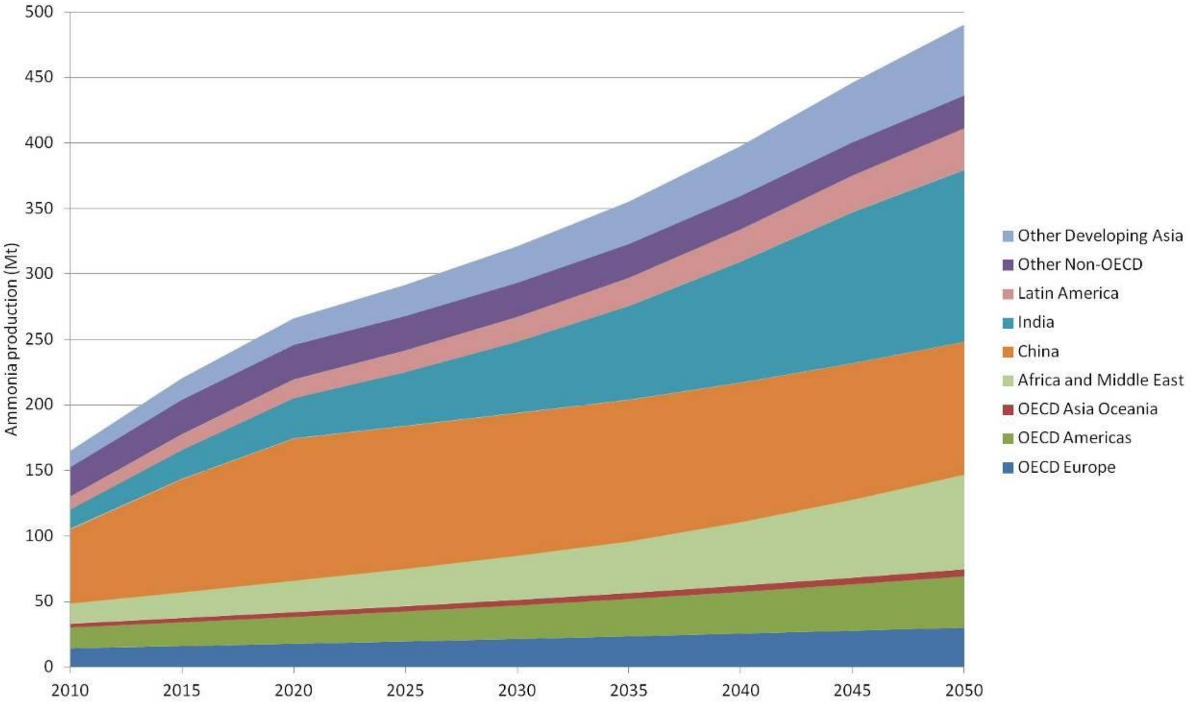

Figure 16. One scenario for the regional shares of ammonia production to 2050 (IEA ETP 2012 2DS low demand)

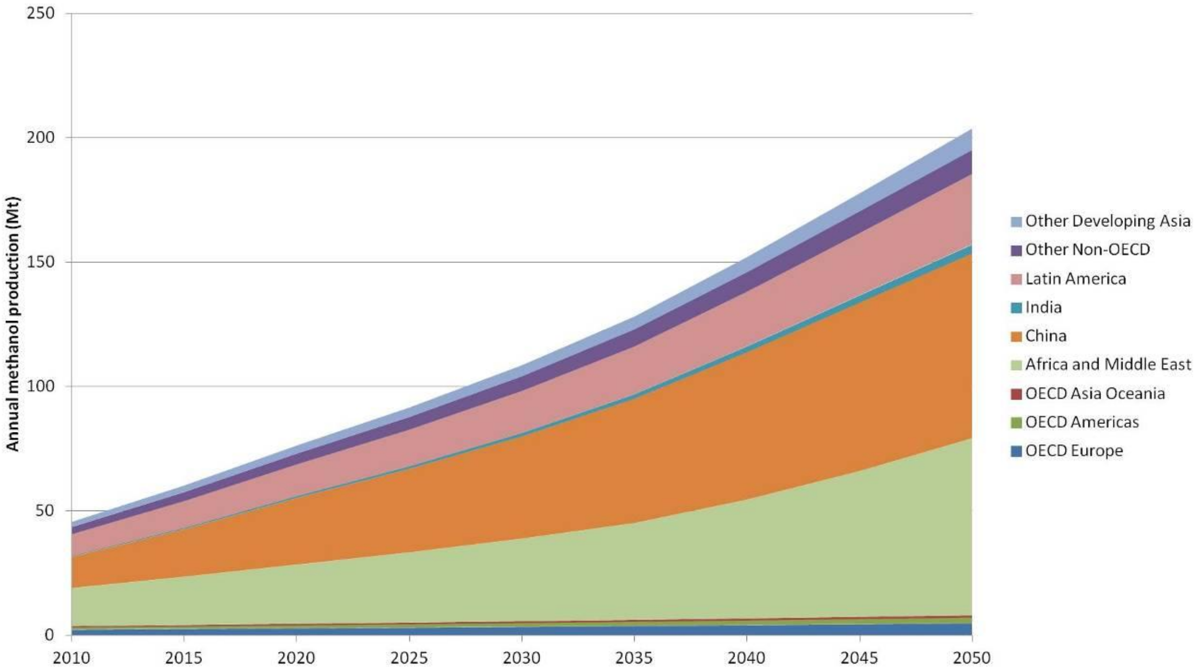

Figure 17. One scenario for the regional shares of methanol production up to 2050 (IEA ETP 2012 2DS low demand)

Australia

Australia does not have a petrochemical industry but does have some ammonia and methanol production. Ammonia production is 1.5 Mt/yr, which is 0.7% of world consumption and 2.6% of Chinese production; Australia ranks 18th in the world (FIFA, 2010). In 2006, the then world's largest ammonia plant was opened with a natural gas-based capacity of 0.76 kt ammonia/yr, now 0.85 kt. The output is mostly exported and not used locally for urea. Australia has also been looking at developing methanol plants to utilise gas reserves for the past decade, but to date only 60 kt/yr methanol plant is operational.

Activities: The Collie Urea Project is a 3.5 Mt ammonia/yr project based on coal gasification which plans to store 2.5 $MtCO_2$/yr as the basis for the Collie hub CCS project. The CCS part of the project was scheduled to start operation in 2015 and had received AUD 52 million in federal government awards, but is currently on hold pending resolution of a legal dispute.

Canada

Canada produced 4.6 Mt of ethylene (plus 0.6 Mt propylene) in 2010 and 1.1 Mt of ethylene oxide (SRI, 2011). Overall capacity utilisation was 83%. The ethylene crackers are mostly ethane-based, and some crackers designed for crude oil processing are under conversion to become feedstock flexible, which should lower process emissions and enable utilisation of ethane from the Marcellus shale basin. Output grew during the past decade, and the limitations on capacity expansion that related to gas supplies from Alaska have now been lifted due to availability of feedstock from shale gas deposits. Methanex, the world's largest methanol producer, has a 0.5 Mt methanol/yr plant in Canada that it restarted in 2011 to take advantage of low gas prices. The plant had not been operating in two previous years. Canada produces 4.9 Mt ammonia/yr, which is approximately 12% of global supply and is economically important to the Canadian economy. Almost all of the eleven ammonia plants are located in Western Canada, the largest being 1.1 Mt/yr and seven others above 0.45 Mt.

The plants are all based on steam reforming of natural gas and are all integrated with urea facilities.

Activities: In Alberta, 0.5 $MtCO_2$/yr from an ethylene plant is already used by Numac for EOR. In addition, Enhance Energy's Alberta Carbon Trunk Line includes plans to use CO_2 captured at an Agrium Inc. fertilizer production facility.

China

Production of ethylene, propylene and ethylene oxide in China in 2010 was 13.6 Mt, 12.0 Mt and 2.7 Mt, respectively (SRI, 2011). Chinese crackers use mostly naphtha, including the world's largest site at 2.9 Mt/yr, but there is also a 300 Mt coal-to-olefins plant that is the first of its kind in the world. Capacity additions have been rapid in the last few years, with 5.5 Mt of ethylene capacity added since 2009 to take total capacity to 17 Mt. However, unlike other major economies, China is a major importer of ethylene and imports are increasing – up to around 1 Mt – mainly from the Republic of Korea and Japan. Chinese methanol production was 15.5 Mt and ammonia production was 40.9 Mt in 2010 (SRI, 2011). Methanol production has doubled in the last decade but demand outstrips supply in China due to fuel standards that enable blending of up to 85% methanol with gasoline. Most Chinese methanol production is coal-based and this limits the overall potential for emissions reductions. The future for an expansion in methanol fuel is uncertain and dependent on gasoline supplies. Ammonia production, on the other hand, is likely to continue to grow and is projected to grow by 20% over the next twenty years from 50 Mt/yr today to supply fertiliser for a growing population. While ammonia capacity in China at 64 Mt/yr is a third of the world total, ammonia plants in China vary widely in size with most plants around 0.1 to 0.3 Mt/yr and the largest at 0.85 Mt/yr. 79% of capacity is coal-based and the rest is natural gas based (CNCIC, 2011). However, overall capacity utilisation is low, at around 62%, so consolidation is expected.

Activities: In May 2007 Dow and Shenhua announced plans for coal-to-chemicals complex at the Yulin chemical plant in Shaanxi Province, China. The project aims to convert coal to methanol to produce ethylene and propylene, and could capture between 5 and 10 $MtCO_2$/yr by 2015 (IEA/CSLF, 2010).

France

Production of ethylene, propylene and ethylene oxide in France in 2010 was 2.7Mt, 1.9Mt and 0.2Mt, respectively (SRI, 2011). Ethylene crackers in France operated at about 80% capacity in 2010. Due to recent high naphtha prices and low ethylene prices due to overcapacity, ethylene plant margins are very low and the French petrochemicals sector is unlikely to expand and may further contract. However, French crackers are sufficient in size for CCS, with the largest being 0.5 Mt ethylene. France does not produce substantial volumes of methanol, but is an importer. Demand for methanol for biodiesel production is growing. Ammonia production was 0.97 Mt in 2010, half of which was produced at the urea production plant in Le Havre, from natural gas. The other 5 plants have capacities of 0.35 Mt or less (IFDC, 2008).

Activities: Although Ammonia production at Le Havre does not appear sufficient to warrant a standalone CCS facility, 0.18 $MtCO_2$/yr are part of the plans to create a CCS hub at Le Havre. However, this has not yet reached beyond the planning phase.

Germany

Production of ethylene, propylene and ethylene oxide in Germany in 2010 was 4.8 Mt, 3.5 Mt and 0.8 Mt, respectively (SRI, 2011). Ethylene crackers in Germany operated at about 80% capacity in 2010, but the sector faces the same challenges as in France in the longer term. In 2005, Europe's first grassroots ethylene plant since 1994 was proposed at Wilhelmshaven but the project was discontinued in 2007 due to rising capital costs. Germany's largest cracker site has a total capacity of over 1.3 Mt ethylene and other sites are sufficient in scale for CCS. Germany produced 1 Mt methanol in 2010, down from 1.4 Mt in 2009 mainly due to a large 0.7 Mt plant being offline. Germany provided around 40% of European methanol demand (SRI, 2011), but also imported a substantial volume. German methanol production is based on refinery by-products, mainly heavy fuel oil. Since the availability of cheap feedstock for methanol production in Germany is limited future growth will most likely lead to higher imports. Germany is also Europe's largest ammonia producer, with 3.3 Mt in 2010. Germany's 6 ammonia sites mostly use steam reforming, although there is some gasification of heavy oil residues. The largest ammonia sites are 1.1, 0.9 and 0.7 Mt ammonia/yr.

Activities: There are currently no projects on CCS in the German chemicals sector.

Japan

Production of ethylene, propylene and ethylene oxide in Japan in 2010 was 6.7 Mt, 5.8 Mt and 0.7 Mt, respectively (SRI, 2011). Ethylene crackers in Japan operated at about 90% capacity in 2010 and output was exported to China despite the economic downturn. The outlook for Asian ethylene demand is strong and exporters in the region look set to benefit. The largest of Japan's 15 naphtha-based ethylene crackers are 0.77 Mt and 0.60 Mt ethylene/yr, and all others are over 0.37 Mt ethylene/yr (OGJ, 2012). Japan has no methanol production plants. Japanese ammonia production was 1.2 Mt in 2010, based on steam reforming and used for urea production. This is a capacity utilisation of just 66%. All Japanese ammonia plants are 0.35 Mt or under.

Activities: There are currently no projects on CCS in the Japanese chemicals sector.

Republic of Korea

Production of ethylene, propylene and ethylene oxide in South Korea in 2010 was 7.5 Mt, 5.7 Mt and 1 Mt, respectively (SRI, 2011). Ethylene crackers operated near full capacity in 2010 (APPC, 2010). The outlook for Asian ethylene demand is strong and exporters in the region look set to benefit but recent price reductions have caused some plant to run at reduced capacity in 2012. South Korea's petrochemicals are largely naphtha based and the largest cracker is 1.85 Mt ethylene/yr. Other crackers are also world scale 0.7 Mt and above. South Korea does not have a significant methanol industry, producing just 12 kt in 2010. Ammonia production is also minimal, just 0.1 Mt/yr at one small site.

Activities: There are currently no projects on CCS in the chemicals sector of the Republic of Korea.

Mexico

Production of ethylene, propylene and ethylene oxide in Mexico in 2010 was 1.1 Mt, 0.5 Mt and 0.3 Mt, respectively (SRI, 2011). Ethylene crackers in Mexico operated at about 80% capacity in 2010. A new cracker based on petroleum gases and natural gas in scheduled to start up in 2015 with a capacity of 1 Mt/yr. Another cracker with 0.5 Mt/yr capacity based on ethane is also being considered but may depend on shale gas developments in the United States Mexico does not have a significant methanol industry, producing just 26 kt in 2010.

Ammonia production has doubled since 2005, reaching 0.9 Mt in 2009, which is the full capacity of its new newest units, but only 50% capacity if idling older plant is included. Production is 50% of that in the 1990s due to competition from the United States and Latin America. The ammonia is predominantly used for urea manufacture. Mexico imports more fertilisers than it produces.

Activities: There are currently no projects on CCS in the Mexican chemicals sector.

Norway

Production of ethylene and propylene in Norway in 2011 was 0.48 Mt and 0.66 Mt, respectively. Norway's only ethylene cracker (0.55 Mt/yr) based on ethane operated at about 85% capacity in 2010. The cracker was recently expanded by 22% and other Norwegian cracker plans are on hold due to market conditions and feedstock availability. Methanol production in Norway is around 0.9 Mt/yr, produced at one plant that uses natural gas and is Europe's largest. Norway's ammonia production was 0.4 Mt/yr in 2010, produced at one plant operating at 70% capacity, which does not produce urea but uses the ammonia to produce NPK fertilizers and nitric acid. The production of NPK fertilisers is undergoing expansion to supply export markets.

Activities: There are currently no projects on CCS in the Norwegian chemicals sector.

South Africa

Production of ethylene and propylene in South Africa in 2011 was 0.56Mt and 0.86Mt, respectively. Cracker utilisation was around 95% in 2010. South Africa's olefin capacity is based on coal, and results from the non-gasoline and non-diesel components of the CTL plants. This does not make the crackers a better candidate for CCS, however, as the feedstock for the crackers is broadly same as other LPG and naphtha crackers. Methanol production in South Africa is approximately 0.14 Mt/yr, produced at one plant as a by-product line of the conversion of coal to petroleum waxes. South African ammonia production was 0.55 Mt in 2010. South Africa has two 0.33 Mt coal-to-ammonia plants that supply non-urea based fertilisers. Urea-based fertilisers are imported to South Africa.

Activities: There are currently no projects on CCS in the South African chemicals sector.

UAE

UAE's 0.6 Mt/yr ethane-to-ethylene cracker was expanded in 2010 with the world's largest cracker to a total of 2.1 Mt/yr and the site is being expanded further to include a third cracker. Methanol production in UAE is being considered to take advantage of higher margin export markets for natural gas based products, but this will be dependent on the outlook for methanol as a transport fuel. UAE ammonia production in 2010 was around 0.44 Mt/yr at one production site operating near full capacity.

Activities: There are currently no projects on CCS in the chemicals sector of the UAE.

UK

Production of ethylene and propylene in the UK in 2011 was 2.23 Mt and 0.76 Mt, respectively. Cracker utilisation was around 80% in 2011. UK crackers are naphtha-based and the sector faces the same challenges as in France and Germany in the longer term, especially with the continuing decline of North Sea oil and gas production. The UK has three crackers over 0.7 Mt ethylene/yr, all of which are on the North Sea coast, the largest being 0.87 Mt ethylene/yr. The UK is not a methanol producer, but does have ammonia plants. In 2010 around 1.5 Mt ammonia were produced at four sites based on natural gas, the largest of which is 0.55 Mt and the smallest of which is 0.26 Mt. These plants are not integrated with urea production.

Activities: The 0.27 Mt ammonia plant at Hull is considered part of the second phase of the Yorkshire CCS cluster concept, but is unlikely to be integrated until the late 2020s at the earliest.

United States

Production of ethylene, propylene and ethylene oxide in the United States in 2010 was 24.0 Mt, 14.1 Mt and 2.6 Mt, respectively (SRI, 2011). Ethylene crackers in the United States operated at about 87% capacity in 2010. The United States has 37 crackers, based on a mixture of feedstocks. Over two-thirds are larger than 0.6 Mt ethylene/yr, of which seven are naphtha-based, one is gas oil based and the rest are a mixture of ethane and LPG. Almost all United States cracker capacity is located in Louisiana and Texas (OGJ, 2012). Numerous cracker capacity expansions based on ethane and LPG have been announced in the past year due to the shale gas boom, but it is not clear whether or not some existing capacity will be displaced. In addition, two projects for new 1.5 Mt/yr grassroots crackers are under consideration. If all projects go ahead United States cracker capacity would be increased by 28% by 2017. Many of these projects would be ethane-based and thus could have lower CO_2 emissions than existing plants. United States commercial methanol production in 2010 was 0.8 Mt, 75% based on natural gas, mostly at one site (Sayah *et al.*, 2012); but coal-to-methanol has been commercial at Kingsport since 1983. As recently as 1998, there was 9.6 Mt of methanol capacity but rationalisation and fuel costs mothballed United States and European plants in favour of imports. One new facility is being planned by a downstream user to provide competition. Ammonia production was 8.3 Mt at 22 sites, based on natural gas. The largest site is 2.1 Mt/yr, and this is partly integrated into urea production, and three other sites are around 1 Mt/yr. Most other sites are around 400 to 500Mt/yr (IFDC, 2008). Around one third of United States ammonia demand is met with imports. United States ammonia plants were operating below capacity (77% on average) due to the cost of fuel but shale gas may change this outlook.

Activities: The Enid Fertilizer plant in Oklahoma has captured over 0.6 $MtCO_2$/yr since 2003 for use in EOR. A CCS project is being proposed at the Coffeyville Resources petroleum coke gasification-based ammonia and urea ammonium nitrate production facility in Kansas to capture around 0.6 $MtCO_2$/yr for use in domestic EOR and/or geological storage. The Texas Clean Energy Project (TCEP) is a large scale commercial coal gasification power/polygen project near Odessa, Texas. In addition to power it plans to produce ammonia from coal and capture 2.5 $MtCO_2$/yr (90% of the CO_2) for EOR from 2015. The total cost will be over USD 2.5 billion. The Hydrogen Energy California (HECA) project in California is also a polygeneration project that plans to capture 3 $MtCO_2$/yr from 2017. The Leucadia demonstration project for methanol production based on petcoke plans to capture 4.5 $MtCO_2$/yr by 2014. TCEP, HECA and Leucadia all have financial support from the Department of Energy totalling USD 888 million, not including tax relief measures. There is a biomethanol project in Soperton that does not include CCS but indicates a potential low-CO_2 pathway to United States methanol production.

Summary

The chemical sector is highly diverse, but the potential for CCS can be better understood by looking at the size of the CO_2 sources at a chemical site; the partial pressure of CO_2 in the off/flue gas, and the downstream dynamics of the industry.

Among the sources considered here, methanol is a liquid and is a globally traded commodity. Many major economies rely entirely on imports as their own natural resources do not enable competitive production. As a result, methanol plants are often large and these are highly suitable for CO_2 capture, especially if based on coal. Ammonia, on the other hand, is a strategic industry that exists in most countries, but plants can be relatively small and the integration with urea production very strongly influences the ultimate amount of CO_2 produced. Consequently, CO_2 capture from ammonia production looks attractive only for coal-based plants in China and South Africa, as well as new gasification based projects in Australia, the United States and, potentially some others. There are several gas-based ammonia plants elsewhere in the world that appear interesting from the perspective of clustering CO_2 sources, especially where they are not integrated with urea production.

Process CO_2 emissions from world-scale ethylene oxide plants are good candidates for CO_2 capture where they can be combined with other local CO_2 sources, such as high purity CO_2 from hydrogen production. However, it is ethylene crackers that offer the most potential for CCS in petrochemicals. The flue gases of almost all commercial crackers based on naphtha, and world-scale plants based on ethane and LPG, would enable CO_2 capture at a scale of over 0.5 $MtCO_2$/yr. The greater efficiencies introduced by recycling the flue for fuel efficiency in future plants could be offset by their larger size. However, capture on a cracker would require the availability of proven flue gas scrubbing techniques and the knowledge of how to integrate it into a chemical site to reduce the parasitic energy cost on site. Capture from some coal-based CHP sources in the chemical sectors of some large economies could also make sense and would encounter the same challenges as capture from crackers. In fact, one conclusion of this analysis is that the availability of proven flue gas scrubbing solutions, combined with sufficient drivers for applying CCS, would make CCS an appropriate climate change mitigation technology for all coal-based chemical sites.

8. Other sectors

Four other sectors have been the subject of study in relation to the particular suitability of CCS for emissions reduction. Some processes in these sectors are already providing high purity CO_2 to pilot CO_2 storage projects and EOR projects and are well understood. Other sectors are closer to the start of their pathway towards substantially reducing their CO_2 emissions.

Gas Processing

Many sources of natural gas contain high percentages of CO_2 that are higher than the market tolerated 2.5% and are removed before the gas is sold[20]. This ‘sweetening’ process is usually achieved by capturing the CO_2 using a solvent. The CO_2 is often vented to

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[20] According to Total, “40% of the world’s remaining gas reserves are sour or acid, with about 10 billion cubic meters containing more than 10% hydrogen sulfide (H_2S) and at least 20 billion cubic meters containing more than 10% carbon dioxide (CO_2)” (Total, 2012). Acid gas can contain CO_2 in concentrations up to 90% by volume.

atmosphere, and therefore the geological storage of CO_2 could significantly reduce the emissions from this sector. In fact, processing of low BTU gas has provided the CO_2 for several of the front runner CO_2 transport and storage projects, including Sleipner and Snohvit in Norway, and In Salah in Algeria. These projects store and monitor 1 $MtCO_2$. 0.7 $MtCO_2$ and 1 $MtCO_2$/yr, respectively. An indication of the low costs of CCS in this sector is provided by the fact that investment decisions for Sleipner (1996) and Snohvit (2008) were taken to avoid a Norwegian carbon tax that has risen from USD 50 to 85 since 1996.

Removal of the CO_2 when processing natural gas has been well-known and commercially applied since the 1950s. The solvents used are generally the same as those used in flue gas scrubbing processes, such as MEA and KS-1, and the CO_2 concentrations slightly lower than in flue gases (Sleipner's gas stream is 9% CO_2) thus requiring slightly more energy input per tCO_2 captured. On the other hand, fewer impurities generally have to be removed in comparison to CO_2 capture from flue gases and a plentiful source of energy is readily available. Although the costs of energy and solvent must be taken into account, the reason that gas processing is considered to be a straightforward opportunity for CCS is that gas sweetening is already undertaken in many locations and the high purity CO_2 vented to atmosphere. Redirecting this CO_2 to storage or utilisation facilities requires only a regulatory or economic incentive and the availability of a suitable transport and storage/usage option.

Among CEM CCUS AG countries, acid gas sweetening is performed in most significant gas-producing regions: Australia, Canada, Norway, UAE, UK, United States Furthermore, shale gases are as diverse in composition as other sources of natural gas and CO_2 levels of 10% are not uncommon. A key criteria for CCS application is the CO_2 production rate at a given processing plant. As a rough indication, a gas stream with 10% CO_2 and 10% H_2S by volume will yield 0.5 $MtCO_2$/yr from production of 2.2 billion m^3 natural gas/yr. For comparison, the Sleipner field produces approximately 13 billion m^3/yr. Consequently, sufficient CO_2 is probably available at a very large number of gas fields, and it is quite possible that gas sources coming on stream in coming decades (e.g shale gases and lower BTU sources in the Middle East) will be more acidic and require processing. However, it is challenging to predict the size of future CO_2 sources from gas processing due to the variability of CO_2 concentrations between gas wells and the uncertainties over whether gas fields with very high CO_2 concentrations (over 50%) will be developed due to social and environmental concerns.

Pulp and Paper

The production of paper and paperboard is a significant contributor to CO_2 emissions in certain CEM CCUS countries, namely Canada, China, Republic of Korea and the United States. The other major global production region is Scandinavia. Emissions originate from fuel combustion for high temperature chemical pulping, mechanical pulping, onsite electricity production and drying. These emissions depend greatly on the fuel used. For example, in Scandinavia the primary fuel input is biomass (73% in Finland and 89% in Sweden) that is available from the forestry feedstock source or the black liquor by-product of the processes (Ecofys, 2009). Other regions use fossil fuels due to local availability and could therefore significantly reduce their lifecycle GHG impact by switching to biomass. In fact, because most climate policies do not recognise bio-derived emissions, switching to biomass from fossil fuels is currently the most attractive mitigation option. Employing CCS will make sense at those plants where fuel switching is not an economic option, where there is a commercial buyer for CO_2, or where an incentive is provided for the capture and storage of bio-derived emissions at plants that have already switched to biomass fuel. Incentives for storing bio-derived emissions are recommended to encourage the lowest emissions avoidance costs regardless of their source (see section on biofuels).

Capture of CO_2 at pulp and paper sites has been studied for Scandinavia. It has been found that the flue gases at a large kraft integrated site (1550 air dried tonnes per day) could be fitted with flue gas scrubbing using amine absorption solvents (Hektor and Berntsson, 2007). The main cost sensitivity has been found to be the way in which this heat is sourced for solvent regeneration, either from combustion of additional fuel, from reduction in electricity generated onsite or from utilisation of excess heat from other processes (Hektor and Berntsson, 2007). Utilising excess heat onsite provides significant cost savings compared to the combustion of additional primary energy. Opportunities for exploiting excess heat are greatest in regions process integration has not been extensively pursued but opportunities have been shown to exist at integrated Scandinavian sites where efficiency measures lead to higher excess heat temperatures (Jonsson and Berntsson, 2012). However, competition with other uses for excess heat from industrial sites, such as district heating, biomass drying or for heat pumps, may increase in the future and place a cost on this heat. The average European kraft mill has annual emissions of 1.2 $MtCO_2$, 90% of which are bio-derived (Carbo, 2011). Other non-integrated mills would generally be considered too small for application of CCS.

One option for significantly improving the GHG performance of the pulp and paper sector could be the introduction of black liquor gasification in combination with combined cycle turbine power production (BLGCC) (IEA, 2012). Gasification of black liquor, like gasification of coal, would yield a stream of relatively pure CO_2 that would easily facilitate capture. However, the prospects for black liquor gasification becoming commercialised by 2030 are not currently promising due to a lack of rapid technical progress, improvements in boiler designs and the development of lignin recovery techniques for energy provision. In addition, absolute volumes of CO_2 from BLGCC would be smaller than from traditional boilers and may be located at a large distance from other industrial clusters, thus limiting economies of scale.

Today, CO_2 is captured from the flue gases at two Swedish pulp and paper mills and is used in the chemical production of precipitated calcium carbonate. No CCS projects exist in the pulp and paper industry.

Food and Drink

Capture of CO_2 in the food and drink sector has been practised for many decades, primarily for the carbonation of drinks which utilises over a million tonnes of CO_2/yr. This CO_2 is sourced from a variety of sources according to local conditions but often from flue gas scrubbing of fossil fuel combustion flue gases using amine absorption solvents followed by additional clean-up. Due to the small scale of these capture plants they neither suffer from problems of scarce local energy nor strong pressure on costs of CO_2 production. It may be possible for larger-scale CO_2 capture plants to supply a slip stream of CO_2 to the beverage industry if the two industries are geographically close. This could assist project economics and undercut existing CO_2 providers, but would be unlikely to make a big impact on CCS costs.

While the soft drink industry uses CO_2, the brewing industry is a major producer of CO_2. The fermentation process releases CO_2 in its conversion of sugars to alcohol. A commercial brewery can produce over 3 $ktCO_2$/yr in process emissions from fermentation and 16 $ktCO_2$/yr from combustion (Olajire, 2012). The world's largest brewery in Mexico is ten times this size. The process emissions can be easily captured, and at many breweries they are captured, purified and returned to the beer to provide additional carbonation. This is cost-effective and avoids buying commercial CO_2. It can thus dramatically reduce the amount of CO_2 that it would be necessary to capture and store. In addition, since the process emissions are biogenic they would not be covered by most climate regulations unless incentives existed for negative emissions schemes (see section on biofuels). The combustion emissions are usually derived from a fossil fuel source and can be captured using flue gas scrubbing techniques.

Biofuels

Liquid and gaseous biofuels can be produced through esterification, digestion, fermentation or gasification. The latter three processes produce relatively pure CO_2 streams. Of these, fermentation is currently used at sufficient scales for CCS. Indeed, a bioethanol CCS project in Illinois, US, plans to store 1 $MtCO_2$ annually from 2015. Anaerobic digestion is generally not performed at a sufficient scale for CO_2 capture, and gasification is not expected to be commercially deployed until next decade. Although the impact of specific impurities should be studied, gasification of biomass for fuel production would facilitate similar CO_2 capture operations to known coal-to-liquids technologies.

Today, climate policies and regulations do not penalise the process emissions of CO_2 from biofuels production because they are biogenic in origin. However, capturing and storing any CO_2 that would otherwise have been emitted should be considered as part of a lowest cost emissions reduction pathway, especially if it is a relatively pure source of CO_2. If the CO_2 stored though bio-energy CCS (BECCS) were to ultimately exceed the CO_2 emitted from fossil sources then the overall effect would be one of removing CO_2 from the atmosphere; so-called 'negative emissions'. The deployment of BECCS to cost-effectively achieve severe reductions in GHG emissions rates has been studied separately from discussions of CCS in industrial applications (IEA, 2011). The findings indicate that there are numerous opportunities for BECCS but that the lifecycle emissions of the biomass production and processing should be accounted for and changes in the incentives for negative emissions would be required. Such incentives should recognise the biofuels sector's existing contribution to climate mitigation, but could also recognise that all point sources of high purity CO_2 emissions are candidates for CCS, especially in sectors that forecast large amounts of new plant in coming decades. Biofuels plants may prove to be more attractive sites for CO_2 capture than those in other industries, and it appears that BECCS deployment will depend heavily on ambitious climate policies and not on technological issues.

Non Ferrous Metals

Globally, in 2010, 164 $MtCO_2$ was emitted from the production of 42 Mt aluminium and 330 $MtCO_2$ were emitted from the production of electricity imported to power the electrolysis process, despite a large proportion of this coming from hydro power. Despite increased recycling and use of scrap, global primary aluminium production grew at 3.6%/yr between 2000 and 2010 (EERE, 2007). China, Canada, the UAE, the US, Australia, South Africa and Norway are all in the world's top ten aluminium producing countries. China produces 40% of the world's primary aluminium and over 4 times the amount of aluminium as Russia, the second largest producer.

The reduction of alumina with carbon produces CO_2 process emissions of 1.2 tCO_2/t of aluminium (EERE, 2007). In Australia, CO_2 is imported by an alumina refiner to treat bauxite waste, which results in the permanent chemical trapping of 80 $ktCO_2/yr$ but the opportunities for this to process to act as a CO2 sink are too limited to have a significant impact on global emissions reduction from the sector. The dominant CO_2 emissions source is indirect, from generation of the electricity used in aluminium smelting. Consequently, aluminium production is located in proximity to large, low cost, baseload electricity supplies and 50% of the electricity used to produce aluminium globally is hydropower. Between 2000 and 2010, 80% of the growth in smelting capacity was in China. The key to major CO_2 reductions from aluminium smelting is the availability of low carbon electricity. CCS looks likely to be a key facilitative technology in regions where fossil fuels will continue to be used to power aluminium smelters and consequently the aluminium industry appears to have a strategic interest in ensuring that CCS will be available to minimise costs in a higher carbon price future. However, the aluminium sector is currently suffering from overcapacity and thus unprofitability in many regions; the coming decades are likely to see closures of small CO_2-intense plants in CCUS AG countries. As a result, the aluminium sector could be engaged in cross-sectoral efforts to advance CCS, including CCS from power generation, but should not be expected to be a leader.

9. Common opportunities and challenges

This background paper has summarised the state of knowledge of how deep reductions in CO_2 emissions might be made in several key industrial sectors using CCS and how this is affected in CCUS countries by plant size, technology choices and likely commercial developments. One clear conclusion is that despite a common tendency for analysts to group industrial applications for CCS together, this categorisation risks grouping together a variety of different sectors and processes for which CO_2 capture faces very different technical, economic and political challenges. CCS solutions for industrial applications are far more varied than CCS solutions for the power sector and this must be recognised by policymakers. On the other hand, this background paper points to a number of conclusions that indicate common opportunities and challenges.

1. *There are many opportunities for technology transfer between sectors, especially for flue gas scrubbing.*
   A number of sectors (gas processing, chemicals, refining) already separate large volumes of high purity CO_2 and these should be targeted for early projects that can provide vital crossover knowledge about transport, use and storage of CO_2. Other sectors have the chance to redesign their processes to improve overall efficiencies, or increase the flexibility of fuel use. These sectors need specific experience of operating these new processes at scale before their potential can be fully understood. Most processes with CO_2 flue gas partial pressures of 100 kPa or below are suited to flue gas scrubbing using absorption solvents. While this approach can be costly in terms of additional energy required, site specific cases should be investigated for availability of excess heat that can reduce this cost. Furthermore, flue gas scrubbing at the end of the process can avoid the technology risks of redesigning

plants and presents many opportunities for learning between sectors to develop better solvents – or innovative capture processes – and optimise their use for a variety of CO_2 partial pressures. Another opportunity is to be found in the prevalence of hydrogen among the various technology summaries as either a future fuel or reducing agent. Although economies of scale may prevent single sectors or plants from switching to use of hydrogen, centralised hydrogen production facilities (using natural gas, coal or biomass feedstocks) and operating large-scale CCS, could supply integrated sites with hydrogen for the generation of power, the reduction of iron ore, the production of ammonia, the production of methanol, or the upgrading of liquid fuels. This would address process emissions in these sectors and would considerably reduce the level of risk that would accompany plant redesign to facilitate CO_2 capture in individual sectors. Table 3 presents the technology summaries and indicates similarities for technology transfer between sectors.

2. *The size of a site's emissions, or the emissions from a sector in a country, is not a good indication of the potential for CCS.*
   It is clear from this analysis that certain processes do not produce CO_2 streams that would be large enough or concentrated enough to make CCS attractive on a single plant. Furthermore, individual sites can have several emissions sources, only some of which make sense for CCS, which reduces the total possible emissions avoidance below the notional capture rate of the capture technology (e.g. steelworks). This also arise in the case of downstream uses of CO_2 (e.g. ammonia and methanol) and the fact that even large modern commercial plants do not always promise captured CO_2 streams of higher than 0.5 $MtCO_2$/yr. A country with a very large number of small scale producers using natural gas may not be able to apply CCS at all in the sector, whereas a country with a small number of large CO_2 intensive producers may be able to apply CCS at each site to avoid the majority of the emissions. It should be noted that the 0.5 $MtCO_2$/yr scale used in this paper is purely indicative of the smallest size that is likely to offer sufficient economies of scale for a CCS project during the early stages of deployment of CCS. Useful pilot and demonstration projects in these sectors could be smaller than this size and should be sized in accordance with available funds and value of the incremental learning delivered. During later stages of CCS deployment, where the emergence of 'clusters' and 'hubs' could be envisaged, smaller capture plants would be able to benefit from the economies of scale of the CO_2 transport and storage solution for the whole cluster.

3. *The application of CCS to plants that use natural gas, oil or coal-based feedstocks could all be highly attractive for emissions reduction in the sectors.*
   It has been seen that in many sectors the feedstock or fuel input can vary between regions. Due to the lack of alternative energy supplies and feedstocks for these sectors, CCS appears to offer a unique emissions mitigation option even for plants using lower carbon inputs, such as process heaters using natural gas or crackers using ethane. However, plants operating using lower carbon inputs may generally need to be world scale to make CO_2 capture a realistic option. On the other hand, CCS for coal-based processes appears almost universally attractive. Expansion of coal-to-liquids, coal-based chemicals and processes using coke as a reducing agent could warrant special attention with regard to the future application of CCS.

Sector	No.	CO_2 capture technology	Current technology	Scale of operation today ($ktCO_2$/yr)	Technical Readiness Level (TRL)[21]	Potential Impact (Scale: 1-9)	Similarities with other capture technologies
Iron and Steel	1	BF/BOF flue gas scrubbing	Amine solvent	10	7	Very high	6, 8
	2	BF/BOF TGR	PSA	4.4	5		8
	3	DRI	Physical solvent	80	8	Medium	4, 13
	4	Smelting	Physical solvent	0	8	Low	3, 13, 14
Refining	5	Hydrogen	PSA	450	8	Medium	10, 12, 17
	6	FCC	Amine solvent	75	6	Low	1, 8
	7	Process heaters	Amine solvent	103	6	High	11
Cement	8	Kiln flue gas scrubbing	Amine solvent	12	6	Very high	1, 2, 6
	9	Oxy-firing	Cryogenic	0	6		15, 16
Chemicals	10	Ammonia	PSA	675	8	Medium	5, 12, 17
	11	Ethylene	Amine solvent	500	7	High	7
	12	Methanol	PSA	<100	8	High	5, 10, 17
Gas processing	13	Sweetening	Physical solvent	8500	9	Medium	3, 4, 14
Aluminium	14	Smelting (direct)	Amine solvent	0	7	Low	3, 4, 13
Food and drink	15	Fermentation	Cryogenic	<100	8	Low	9, 16
Biofuels	16	Fermentation	Cryogenic	<100	8	High	9, 15
	17	Gasification	Physical solvent	0	2	Medium	5, 10, 12

Table 3. Summary of technology options for CO_2 capture in industrial applications and opportunities for technology transfer

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[21] Following the 1 to 9 scale for TRLs developed by NASA and recently applied to CCS (EPRI, 2008; Rubin *et al.*, 2012). The Global CCS Institute has used the TRL scale to measure progress in CO_2 capture for power plants and a similar approach is taken here to extend it to industrial applications (GCCSI, 2012).

4. *There is a lack of knowledge about emissions sources that are located in geographical proximity to one another and which could be clustered together.*
   The flipside of Conclusion 2 is that CO_2 sources of under 0.5 $MtCO_2$ could potentially be clustered together at sites that contain a number of different sectors and CO_2 sources. For sources over 0.5 $MtCO_2$, clustering could improve the economics of CO2 transport and storage considerably. However, if the sources are not in close proximity then such a strategy would need to overcome issues of pressure drop between sites and may require additional pressure booster stations in the pipeline route. Furthermore, clustering CO_2 sources raises issues of pipeline usage contracts and third party access. Transport and storage have not been explicitly considered in this paper but there is evidently a dearth of knowledge about suitable storage capacities near potential CO_2 hubs, such as ports and petrochemical sites.

5. *Overcoming shortages in excess steam on industrial sites will be a crucial factor in realising CCS in industrial applications.*
   Installing amine-based flue gas scrubbing demands a supply of heat for solvent regeneration. In the power sector this steam can often be provided by an off-take from the turbines but in industrial applications this could require the construction of additional steam-raising facilities and increase capital costs. The success of CCS in industrial applications may rest on the ability to overcome this requirement. On one hand, using available low grade heat from the plants or adjacent plants to supply the solvent regeneration process would exploit the lower technology risk associated with flue gas scrubbing and take advantage of synergies between flue gas scrubbing approaches in the different sectors. On the other hand, as can be seen from this paper, the need to reduce steam requirements has stimulated innovations specifically targeted at CO_2 capture in industrial applications, but which would require more complex and undemonstrated plant designs. The most effective innovations will be those that reduce the heat and/or pressure required for CO_2 capture and compression, increase the CO_2 concentration in the flue- or off-gas, or introduce novel tailored capture methods, without necessitating radical process changes in the sectors involved at the same time as the introduction of CCS,

This background paper has been based on desktop analysis of existing publications. It seeks to gain agreement among CCUS AG Working Group members on the technological opportunities and the current state of the sectors in CCUS countries. While every attempt has been made to be as comprehensive as practicable, input is sought on different perspectives or additional sources of information.

To progress this work to the point where recommendations for opportunities and policies to advance CCS in industrial applications in the near-term, this paper is to be complemented by the results of stakeholder interviews and discussions. These discussions will focus on matters of political and corporate priorities, appetites and concerns in the area of CO_2 mitigation in the coming 10-15 years.

Paper prepared by Simon Bennett, IEA. 17 January 2013.

Annex I - Definitions

2DS	The IEA's 2 Degree Scenario for a lowest-cost pathway to 2050 for limiting global temperature rises to 2 degrees.
ADNOC	Abu Dhabi National Oil Company
AUD	Australian dollars
BBL	One standard barrel of oil, 159 litres, approximately 137kg of oil equivalent
BF	Blast Furnace
BOF	Basic Oxygen Furnace
BTU	British Thermal Unit (a measure of energy content)
CAD	Canadian dollars
CEM	Clean Energy Ministerial. Participating CEM governments are: Australia; Brazil; Canada; China; Denmark; European Commission; Finland; France; Germany; India; Indonesia; Italy; Japan; Korea; Mexico; Norway; Russia; South Africa; Spain; Sweden; United Arab Emirates; United Kingdom; United States.
CCS	Carbon (or CO_2) Capture and Storage. Refers only to processes that provide long-term isolation of CO_2 from the atmosphere for climate mitigation reasons. Can be combined with use of the CO_2 where there are provisions for the long-term confinement of the CO_2.
CCSA	Carbon Capture and Storage Association
CCUS	Carbon (or CO_2) Capture, Use and Storage. Includes the use of CO_2 as a feedstock or aid to hydrocarbons production.
CCUS AG	Carbon Capture Use and Storage Action Group. Participating CEM governments are: Australia; Canada; China; France; Germany; Japan; Korea; Mexico; Norway; South Africa; United Arab Emirates; United Kingdom; United States.
CHP	Combined Heat and Power
CONCAWE	Conservation of clean air and water in Europe
CNBM	China National Building Material Company Limited
CSI	Cement Sustainability Initiative of the WBCSD
CO_2	Carbon Dioxide
DRI	Directly Reduced Iron
EAF	Electric Arc Furnace
ECRA	European Cement Research Academy
EOR	Enhanced Oil Recovery
ETP	Energy Technology Perspectives biennial publication by the IEA
ETS	Emissions Trading System
EU	European Union
EUR	Euro currency
FCC	Fluid catalytic crackers
GHG	Greenhouse Gas
GDP	Gross Domestic Product, the market value of goods and services produced within a country, usually measured on an annual basis
ETS	Emissions Trading System
IGCC	Integrated Gasification Combined Cycle
IEA	International Energy Agency
ISIC Rev.4	International Standard Industrial Classification of All Economic Activities. Revision 4 was released in August 2008.
LKAB	Luossavaara-Kiirunavaara AB (publ). Swedish producer of processed iron ore products for steelmaking.
LPG	Liquefied Petroleum Gases
NER300	New Entrants Reserve. A European Commission funding scheme for CCS and innovative renewables projects, funded by the monetisation of 300 million EU ETS allowances.
PCA	Portland Cement Association (US)

PPM	Parts per million, a measure of abundance of a substance in a sample of mixed substances
PPP	Purchasing Power Parity
PSA	Pressure swing adsorption
R&D	Research and development
SMR	Steam methane reforming
TCE	Tonnes of coal equivalent (29.3GJ)
TGR	Top Gas Recycling
Toe	Tonnes of oil equivalent
ULCOS	Ultra low CO2 steelmaking
US DOE	United States Department of Energy
VSA	Vacuum Swing Adsorption
WBCSD	World Business Council for Sustainable Development

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Annex III - Rationale for not prioritising certain sectors

Sector	Potential emissions profile without CCS	Technical challenges	Political pressures
Extraction of natural gas	More low BTU gas is being extracted, meaning that more CO_2 could be stripped and emitted. The global volumes are not vast, but are significant and this is a growing source of CO2 in the U.S.	No technical challenges to CO_2 capture. The industry has good experience handling CO_2 and the techologies are commercial.	CO_2 venting from gas production is outside the scope of existing carbon pricing regimes (with the exception of Norway).
Manufacture of Food Products and Beverages	Emissions from these sectors are moderate in comparison to the energy-intensive industries (excluding agriculture). The nature of the sectors means that emissions are spread over many sites and only a small number are suitable for CCS on their own (e.g. large breweries) but smaller sites might be able to feed into a pipeline network at low cost.	No technical challenges to capturing CO_2 from fermentation. The CO_2 source is highly pure.	The CO_2 is predominantly biogenic and therefore its emissions are not penalised under existing climate policies.
Manufacture of pulp, paper and paperboard	Emissions are set to increase by around 50% by 2050 without additional strong policy action. Even large mills are much smaller than power plants.	CO_2 capture needs to be tested to investigate suitable solvents for the separation of CO_2 from the specific flue streams.	At many sites, the CO_2 is predominantly biogenic in origin and therefore its emissions are not a focus of existing climate policies and CCS would only be incentivised in a policy regime that recognised the benefits of 'negative emissions'. Sites that use fossil fuels to provide heat and power have the opportunity to switch to biomass fuel inputs as an initial mitigation option. Pulp and paper manufacture on a large scale is limited to a relatively small number of regions.
Manufacture of basic precious and other non-ferrous metals	Process emissions from aluminium production are moderate in comparison to emissions from other energy-intensive industries. Direct and indirect energy emissions	Capturing the CO_2 from aluminium electrolysis presents no technical challenges. Capturing CO_2 from electricity generation is being tackled by power sector	Aluminium plants may be able to meet emissions targets through improving the emissions profile of electricity inputs. The urgency of dealing with process emissions is less

	from aluminium production arise from electricity production, depending on the source of the electricity.	projects.	strong compared to the key sectors.
Manufacture of biofuels (liquids and gases)	All methods of biofuels production release CO_2 and the volumes will grow with the growth of the industry. These emissions do not fully appear in accounting, however, as they are often from biogenic carbon inputs.	Capture of CO_2 from fermentation is well-understood. Biomass gasification is not yet used at a large scale and so it is likely to be another technology generation before the first gasification sites can be built to demonstrate CCS in addition to biomass gasification.	The CO_2 is predominantly biogenic in origin and therefore its emissions are not a focus of existing climate policies and CCS would only be incentivised in a policy regime that recognised the benefits of ‘negative emissions’. Production of biofuels is generally considered to be a sufficient mitigation measure. Work on biofuels in combination with CCS is ongoing in the scope of work on BECCS.

Annex IV – Progression of CO_2 capture plants: first year of operation of next largest plant (area proportional to capture capacity