Zero emissions platform

CO_2 Capture and Storage (CCS) in energy-intensive industries

An indispensable route to an EU low-carbon economy

European Technology Platform for Zero Emission Fossil Fuel Power Plants

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Key conclusions

- If the EU is to achieve its ambition of reducing greenhouse gas (GHG) emissions in line with IPCC[1] recommendations, emissions must be reduced by 80% to 95%[2] by 2050 in order to avoid dangerous climate change. This requires large-scale mitigation actions in *all* sectors of the economy.

- **In 2010, direct emissions from industry accounted for 25% of total EU CO_2 emissions**. Petroleum refining, iron and steel, cement and chemical industries account for 60% of total EU CO_2 emissions from industry.

- Many industrial processes in the EU are operating at or close to the theoretical limits of efficiency, while the release of CO_2 is unavoidable in several manufacturing processes. The adoption of current best available and best practice technologies (BAT, BPT) is therefore not sufficient to achieve EU climate targets.

- **CO_2 capture and storage (CCS) is the only technology that can deliver the deep emission cuts required by several EU energy-intensive industries***.* According to the International Energy Agency (IEA), CCS is the most important technology option for reducing direct emissions from industry, with the potential to mitigate 2 to 2.5 Gt[3]CO_2 per year globally by 2050 – including 0.3 to 0.4 GtCO_2 in the EU27.

- Ensuring a European stake in the global CCS industry will also increase employment in green industries – creating *and* preserving thousands of jobs; while deploying CCS in industries *beyond* power will help **ensure a competitive position for existing EU industries in a future carbon-restrained world** – reconciling EU climate goals with the desired re-industrialisation of the economy.

- Capacity, plant configuration, process arrangement and age can impact the selection of CO_2 capture technologies that could be deployed in an energy-intensive industry.

- Several pilot projects have already validated the technical feasibility of applying CO_2 capture to key processes within many of the relevant energy-intensive industries, including retrofit. It could be concluded that retrofitting CO_2 capture into the operation of the conventional processes is possible. **Large-scale demonstration is now essential** to validate technical and economic factors in a commercial environment.

- In some industrial processes, mainly in the petroleum refining and chemical sectors, the removal of CO_2 is an integral part of the production stream. Such cases could therefore represent **relatively lower-cost CCS projects** compared to processes with dilute CO_2 off-gases – and interesting candidates for early demonstration of the CCS value chain.

- The deployment of **CCS for energy-intensive industries in parallel with fossil-fuel power generation could facilitate clusters** of CCS projects – improving economies of scale for both CO_2 transport *and* storage, and significantly reducing capital costs compared to stand-alone projects.

[1] Intergovernmental Panel on Climate Change (IPCC)
[2] Compared to 1990 levels
[3] Gigatonne = 1 billion tonnes

Key policy recommendations

- For CCS technologies to become widely deployed in energy-intensive industries from 2030, large-scale demonstration projects are urgently required. New technologies in industry must undergo rigorous testing procedures and standardisation in order to ensure safety and reliability.

- CCS in industry can achieve significant CO_2 reductions *beyond* existing EU benchmarks. However, **deployment requires a technological and investment step change via supportive policy mechanisms** – in terms of both direct project funding *and* creating a long-term business case.

- **Stimulating a European CCS supply chain that takes into account emissions from both power *and* industrial sectors** must be a key deliverable of a European CCS policy. This is critical to maximise the contribution CCS can make to the 'green growth' agenda, reducing costs through the stimulation of supply chain competition and securing a European stake in the international CCS industry.

- In many cases, the application of CCS in complex industrial installations will be site-specific. It is therefore essential that **a wide range of bottom-up, techno-economic case studies on different processes and capacities** is undertaken in order to understand the cost-competitiveness of CCS deployment.

- A 2015 global climate agreement may not ensure a level playing field for EU industry. The adoption of the UNFCCC[4] 'common but differentiated responsibilities' precipitates transitory unequal abatement burdens, meaning that zero carbon leakage is beyond reach. **The EU must strive for hard targets in all industrialised nations which represent 'acceptable leakage'** and focus on reducing the costs of abatement to maintain competitiveness.

- In the case of an absent or excessively unbalanced global climate agreement, **border carbon adjustments and sectoral approaches could be carefully assessed** as an option for those governments wishing to take strong unilateral action – and develop and commercialise the global technologies needed to counter dangerous climate change.

The Zero Emissions Platform (ZEP)

Founded in 2005, ZEP represents a unique coalition of stakeholders united in their support for CCS as a critical solution for combating climate change. Indeed, CCS is the single biggest lever for reducing CO_2 emissions – providing almost 20% of the global cuts required by 2050, according to the IEA. Members include European utilities, oil and gas companies, equipment suppliers, national geological surveys, academic institutions, trade unions and environmental NGOs. The goal: to make CCS commercially viable by 2020 and accelerate wide-scale deployment.

www.zeroemissionsplatform.eu

[4] United Nations Framework Convention on Climate Change

1 The necessity of CCS for industrial applications

The critical role of CCS in decarbonising Europe's energy-intensive industrial sectors has recently been recognised by several key institutions. The objective of this report is to shape the debate on CCS in EU industry, providing policymakers with a high-level, state-of-the-art overview of the status of CCS application in four key sectors – highlighting sector-specific research and development needs, while placing the issue within a European and global policy context.

1.1 Direct emissions from industry account for 25% of EU CO_2 emissions

In 2010, industry-related (direct[5]) CO_2 emissions accounted for over 900 megatonnes (Mt) of CO_2 – a quarter of total EU27 CO_2 emissions. As the industrial sectors of iron and steel, cement, chemical production and petroleum refining account for ~60% of EU27 industrial CO_2 emissions, they have been selected as the main focus of this report.

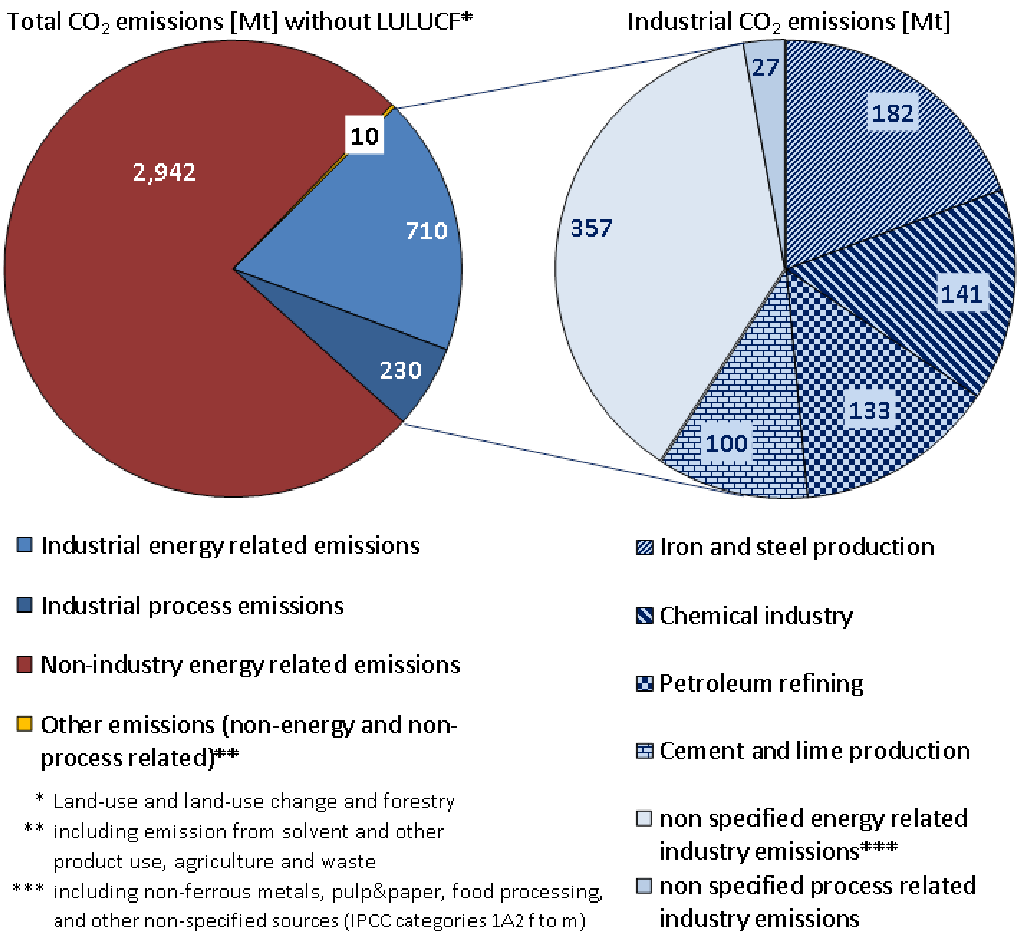

FIGURE 1 EU27 2010 TOTAL CO_2 EMISSIONS AND DIRECT CO_2 INDUSTRIAL EMISSIONS[6]

[5] Excluding emissions related to associated electricity use in industry (indirect emissions)
[6] Using data from UNFCCC National Inventory Submissions, 2012

1.2 CO_2 reductions in the industrial sector are essential to meet EU 2050 targets

In its Fourth Assessment Report, the IPCC stated that in order to keep global warming below 2°C and avoid the most dangerous consequences of climate change, GHG emissions must be reduced by 50% to 85% by 2050 – and peak no later than 2015.[7]

In line with IPCC recommendations for developed countries, the EU therefore has the objective of reducing GHG emissions by 80% to 95% (over 1990 levels) by 2050.[8] In order to meet such a target cost-effectively, CO_2 emissions must be reduced in *all* sectors of the economy. Analysis conducted by the European Commission ("The Commission") has indicated that using a 1990 emission baseline, CO_2 emissions from the industrial sector must be reduced by 34% to 40% by 2030 and by 83% to 87% by 2050.

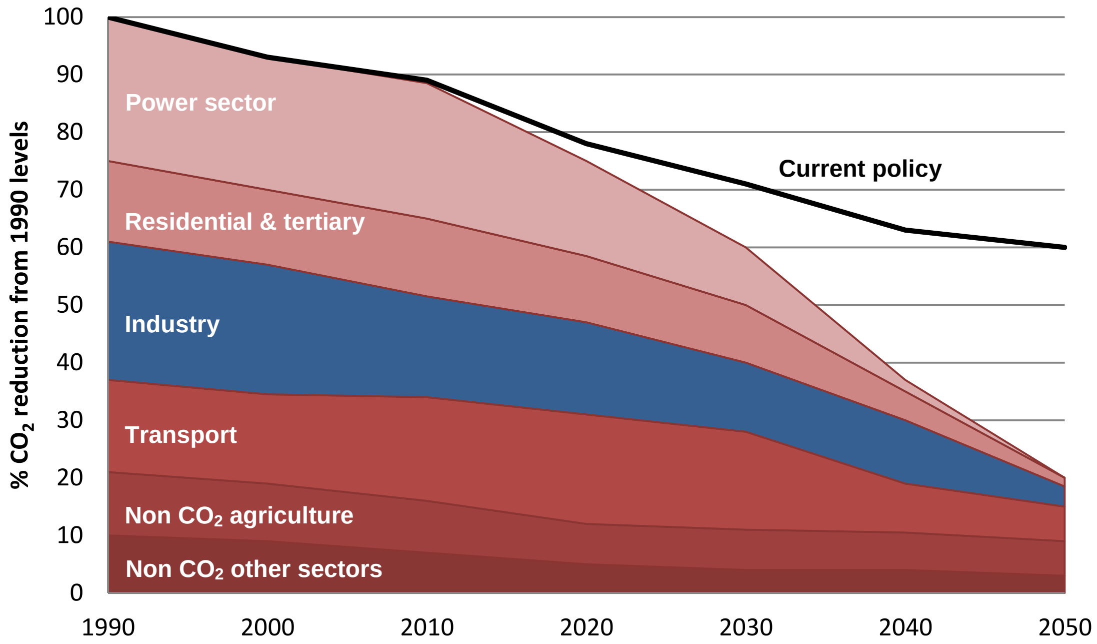

FIGURE 2 **MODELLED EU GHG EMISSION REDUCTIONS TO AN 80% DOMESTIC REDUCTION OVER 1990 LEVELS BY 2050**[8]

1.3 CCS is an indispensable CO_2 abatement pathway for decarbonising industry

The use of advanced energy-efficient industrial processes and equipment, combined with increased recycling, are crucial pathways to reduce resource consumption and GHG emissions from industry. However, many industrial processes in the EU are operating at or close to the theoretical limits of efficiency, while the release of CO_2 is an integral part of several manufacturing processes which cannot be avoided.

The adoption of current best available and best practice technologies (BAT, BPT) are not sufficient to reach the targets set to avoid dangerous climate change. To achieve the drastic reductions in CO_2 emissions needed, the Commission acknowledges that CCS will also need to be widely deployed in industry from 2035.[8]

[7] www.ipcc.ch/ipccreports/ar4-syr.htm, 2007
[8] European Commission, 2011. Roadmap for moving to a competitive low carbon economy.

1.4 Recognition of the necessity of CCS applications in industry is accelerating

To date, applications of CCS in the power sector, in particular for coal-fired power plants, have been the target of the vast majority of research and development, funding and policy initiatives aimed at demonstrating and commercialising the technology. However, in 2011, a joint collaboration between the United Nations Industrial Development Organization (UNIDO) and the IEA undertook a two-year project which produced a set of industry-specific CCS assessments and, ultimately, the "Technology Roadmap: Carbon Capture and Storage in Industrial Applications".[9]

The Clean Energy Ministerial CCUS Action Group – Industrial CCS

Established in 2010, the Clean Energy Ministerial (CEM) is an annual, high-level global forum to promote policies and programmes that advance clean energy technology. Part of the CEM is the Carbon, Capture, Use and Storage Action Group, which aims to create greater political momentum to advance the deployment of CCS. The group requested that expert recommendations be presented on how progress can be made in developing CCS for industrial applications at the fourth CEM meeting in Delhi in 2013. These recommendations,* developed for the CEM by the IEA and the Carbon Capture and Storage Association (CCSA, UK), are summarised below:

- Commit public funds to ~10 pilot and demonstration-scale projects to test the feasibility of CO_2 capture in sectors such as iron and steel and cement.
- Support projects according to their contribution to knowledge, not short-term emission reductions.
- Government should incorporate CCS into forward-looking industrial strategies.
- Start to address competitiveness concerns in relation to energy and climate strategies.
- Exploit synergies between sectors, including the power sector.
- Involve all relevant stakeholders.

* IEA, 2013: Global action to advance carbon capture and storage – A focus on industrial applications: www.iea.org/publications/freepublications/publication/CCS_Annex.pdf

According to IEA analysis, CCS represents the most important new technology option for reducing direct emissions in industry, with the potential to mitigate between 2 $GtCO_2$ and 2.5 $GtCO_2$ per year globally by 2050. This means that CCS in European industrial sectors must abate 0.4 $GtCO_2$ annually by 2050[10] – just under half of the current direct emissions from EU industry.

Indeed, *without* CCS deployed in industrial sectors, emissions reductions to keep global temperature rise below 2ºC cannot be achieved. Unlike electricity production, several industrial sectors lack available options to achieve deep emission cuts in any other way.

[9] www.iea.org/publications/freepublications/publication/name,4004,en.html
[10] IEA, 2012. Energy Technology Perspectives

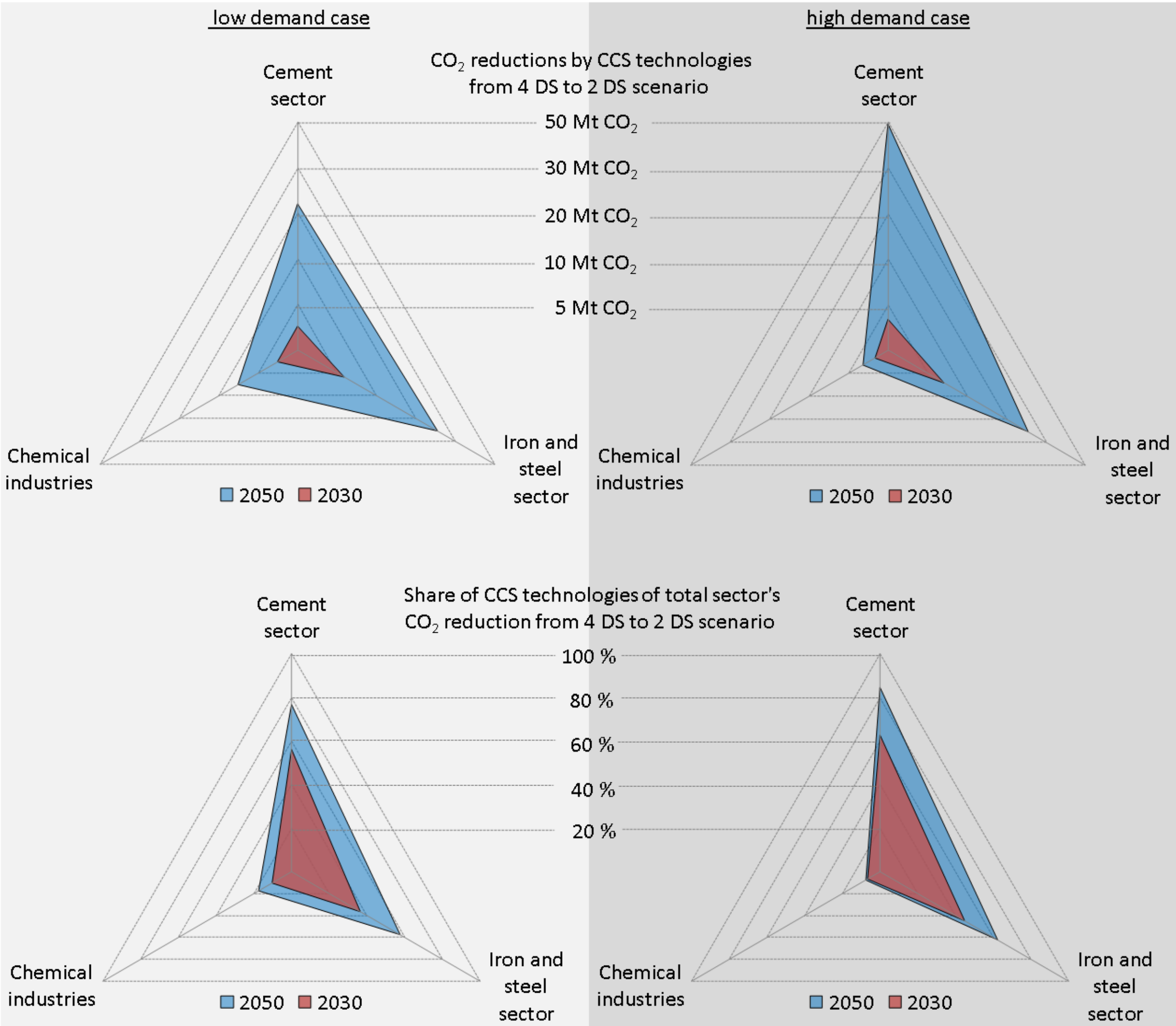

FIGURE 3 THE REQUIRED CO2 ABATEMENT FROM THE IRON AND STEEL, CEMENT AND CHEMICAL INDUSTRIES IN THE EU27 IN 2030 AND 2050 (TOP), SHARE OF CCS CONTRIBUTION TO TOTAL SECTOR CO_2 REDUCTION (BOTTOM)[11]

The results of the IEA's integrated assessment model underpin the relevance of CCS for industrial applications in Europe in reaching a stringent, long-term climate target. In order to reduce GHG emissions from a GHG emission pathway leading to a maximum global mean temperature increase of 4ºC by 2100 (compared to pre-industrial levels – 'the 4 DS scenario'), to a 2ºC stabilisation pathway ('2 DS scenario'), the deployment of CCS differs among industrial sectors in the EU27 (Figure 3).

The contribution of CCS to the GHG reduction from the 4 DS scenario to the 2 DS scenario is highest in the cement branch, accounting for 56% to 63% of its total GHG reductions in 2030 – equivalent to 5 Mt[12] to 7 $MtCO_2$, depending on the demand level. The importance of CCS in mitigating CO_2 from cement production increases towards 2050 and shares rise to between 77% and 85% (32 Mt to 50 $MtCO_2$).

[11] Data has been used from the Energy Technology Perspectives report,[10] graciously provided by the IEA
[12] Megatonne = million tonnes

In the iron and steel sector, CCS accounts for 36% to 45% (12 Mt to 14 MtCO_2) of CO_2 emissions reductions from the 4 DS to the 2 DS scenario in 2030, and 58% to 62% (35 Mt to 36 MtCO_2) in 2050. Compared to the cement sector and the iron and steel industry, the contribution of CCS in reducing direct emissions from the production of chemicals and petro-chemicals is much lower (max. 7% to 17% in the periods 2030/2050), since the main GHG mitigation options relate to energy efficiency and energy recovery measures. Nevertheless, the two latter sectors could offer several low-cost CO_2 capture opportunities when combined with, or connected to, shared CO_2 transport and storage clusters.[13]

Furthermore, it can be assumed that a partial decoupling of the perceived socio-political connection between CCS and coal-fired power plants – with opposition in several EU Member States against coal as an electricity source having led to an opposition to CCS as a climate technology – could help build public support for the critical need for CCS in Europe.

With the consumption of materials such as steel and cement on a steep rise globally – and keeping in mind that these materials are key components for the shift to a green economy (e.g. for construction of renewable energy production and infrastructure), failure to develop ways to reduce these sectors' significant emissions will undermine any efforts to counter global warming.

1.5 Europe's industrial sector must remain internationally competitive

The products of Europe's energy-intensive industrial sectors are openly traded on the global market. International competitiveness is key to ensuring these sectors' economic prosperity, securing European employment and skills, and encouraging innovation throughout industry. The financial and economic crisis since 2008 and the ensuing austerity measures in many Member States have weakened local demand in the automotive, building and construction sectors.

This, in turn, has had consequential effects on EU industrial production, which has not yet recovered to pre-crisis levels in many sectors. Europe faces multiple challenges, particularly the distance to demand from parts of Asia and the Middle East, and a lack of access to relatively cheap energy compared to the Russian Federation and the United States.[14]

While overall EU CO_2 emissions may have reduced as a result of the drop in production, there is little to gain in terms of global emissions reductions by EU industry production being displaced by production elsewhere – especially if such displacement happens in favour of regions with less stringent environmental requirements. Moreover, such a development is likely to undermine EU popular support for climate measures due to the negative employment effects, in turn making it politically unfeasible to introduce such measures. Policies for CO_2 abatement in the EU energy-intensive industrial sector must therefore not be detrimental to European industrial competitiveness.

[13] See section 2.4
[14] CCAP, 2013. The New Deal – An enlightened industrial policy for the EU through structural EU ETS reform. http://ccap.org/the-new-deal-reforming-the-eu-ets-to-enhance-low-carbon-industrial-competitiveness

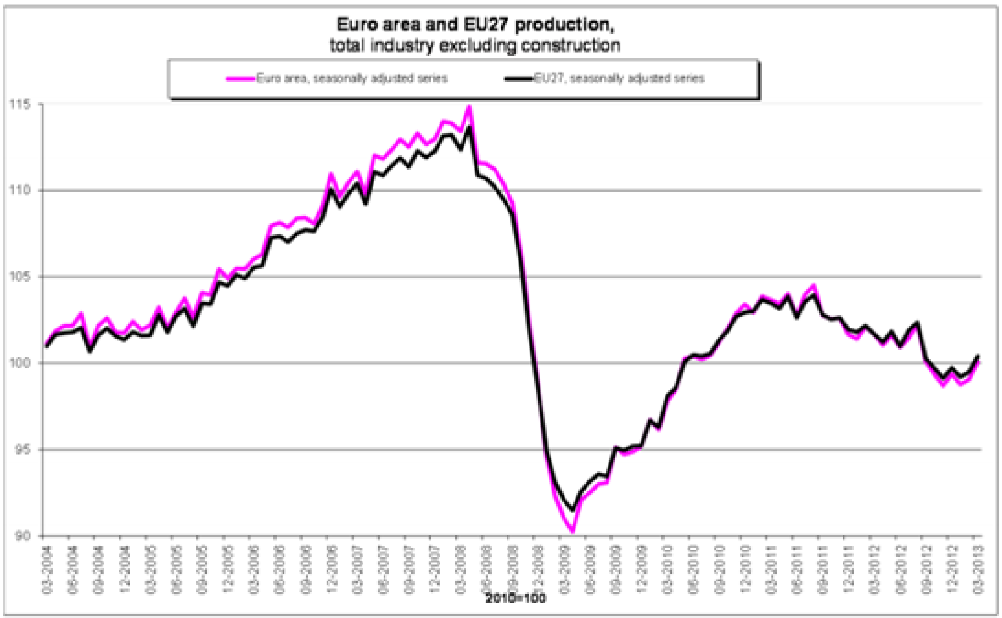

FIGURE 4 EU INDUSTRIAL PRODUCTION INDEX 2004 – 2013[15]

1.6 The ZEP Working Group 'CCS in Other industries'

The Zero Emissions Platform (ZEP) originally focused mainly on the power sector and the decarbonisation of fossil-fuelled power plants. However, after producing a report in cooperation with the European Biofuels Technology Platform (EBTP) on combining CCS with sustainably sourced biomass (Bio-CCS) to attain net *negative* CO_2 emissions,[16] ZEP established a Working Group, 'CCS in Other Industries'[17] in order to broaden the focus to include major energy-intensive industries such as steel, cement, refineries and chemicals.

The goal: to identify synergies in CO_2 capture and other opportunities for cooperation – such as CO_2 infrastructure clusters – in recognition of the IEA's message that around half of the expected CO_2 abatement attained by CCS will take place in industries *beyond* power.

In 2012, the ZEP Working Group 'CCS in Other Industries' was invited by the IEA as a stakeholder in the IEA-/CCSA-led process (see section 1.4), in order to provide EU-specific input to their recommendations for the 2013 Clean Energy Ministerial. This report is a summary of the Working Group's work to date.

[15] Eurostat, March 2013. Industrial production down by 0.4% in euro area and EU27, News release euro – indicators
[16] EBTP and ZEP, 2012. Biomass with CO_2 Capture and Storage (Bio-CCS) – The Way Forward for Europe. www.zeroemissionsplatform.eu/library/publication/206-biomass-with-co2-capture-and-storage-bio-ccs-the-way-forward-for-europe.html
[17] See Annex I for membership of the ZEP Working Group, "CCS in Other Industries"

2 CO_2 Capture and Storage

2.1 CCS could provide almost 20% of global emission cuts required by 2050

CO_2 Capture and Storage (CCS) describes a technological process by which *at least 90% of CO_2 emissions* are captured from large stationary sources (e.g. fossil fuel-fired power plants, certain heavy industrial processes), transported to a suitable storage site, then stored in geological formations – safely and permanently – deep underground (at least 700m and up 5,000m).

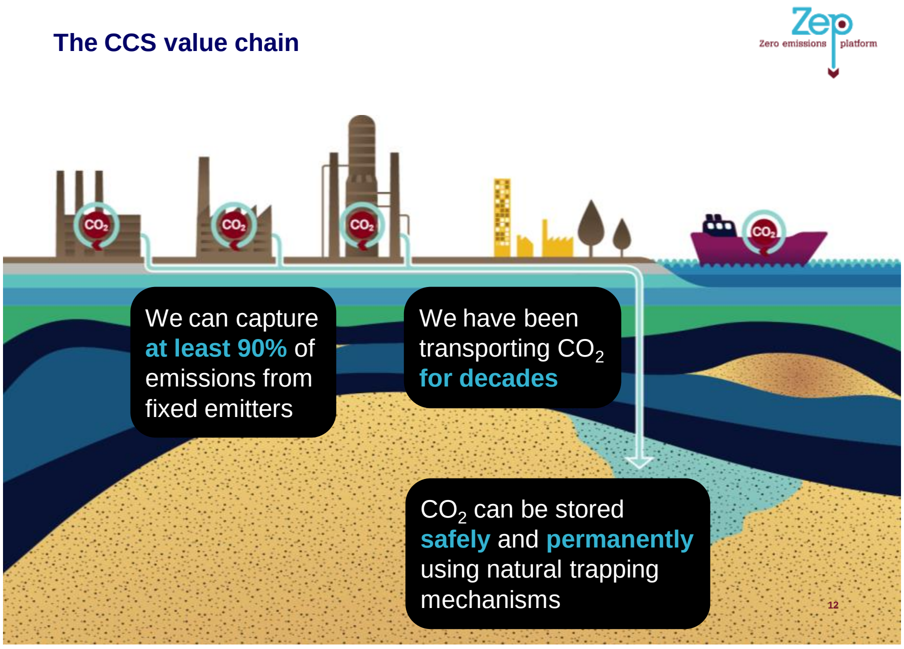

FIGURE 5 CCS IS THE ONLY LARGE-SCALE TECHNOLOGY THAT CAN ABATE 90% OF CO_2 EMISSIONS FROM THE WORLD'S LARGEST EMITTERS

The IEA confirms that "The scale of potential future deployment of CCS is enormous, spanning manufacturing, power generation and hydrocarbon extraction worldwide". Indeed, it is the single biggest lever for reducing CO_2 emissions – providing almost 20% of the global cuts required by 2050. The critical role of CCS in meeting EU climate targets is therefore indisputable – as confirmed by the EU Energy Roadmap 2050 – while the IEA estimates that the costs of achieving global climate objectives *without* CCS would be over 40% higher.

2.2 The application of CCS in industrial processes

Each of the stages in the CCS value chain – capture, transport and storage – can be accomplished in various ways. The heterogeneity of industrial processes may pose challenges, but also opportunities for CCS development.

CO_2 capture routes in industry
There are a number of capture options which could be applied to energy-intensive industrial processes, but it must be noted that the deployment of any capture technologies will in many cases require major or minor alterations in the operation of the conventional process in order to optimise capture efficiency. The bullets below highlight some of the fundamental approaches to CO_2 capture which may be suitable for industry:

- Removal from diluted streams: similar to post-combustion capture from a coal or gas-fired power plant, the CO_2 from diluted gas streams can be captured through the use of chemical or physical solvents.

- Chemical solvents are water soluble components that remove the CO_2 from a gaseous process stream by forming a chemical bond with the CO_2. The CO_2-rich solvent is then heated with steam, releasing the CO_2 and regenerating the solvent. Chemical solvents, such as MEA (mono-ethanolamine) and other amines, are highly effective at removing CO_2 from low pressure and low concentration (i.e. low CO_2 partial pressure) gas streams and lead to a very concentrated stream of CO_2 which can be compressed, transported and stored. However, the solvent regeneration process has a high energy demand (i.e. low pressure steam of 150ºC).
- Physical solvents are liquids that remove CO_2 by physical absorption of the CO_2 into the liquid. The CO_2 load solvent is then subsequently regenerated by pressure reduction, which requires a relatively small amount of energy compared to chemical solvents. Physical solvents require a combination of a high feed pressure with a sufficient CO_2 concentration. The resultant CO_2 stream is pure, however there could be some co-absorption of other gaseous components which may need to be removed.
- Solid sorbents capture (adsorb) CO_2 on their surfaces given a certain temperature or pressure. The CO_2 is then released (or desorbed) through a subsequent pressure or temperature change, which regenerates the original sorbent. Examples of solid sorbents include zeolites, calcium oxide, activated carbon and metal organic frameworks. The processes of temperature swing adsorption (TSA) and pressure swing adsorption (PSA) using solid sorbents are commercially practised methods of gas separation and in certain capture applications can lead to significant energy savings over solvents.

Examples of potential applications of chemical solvents include conventional cement kilns and blast furnaces, or boilers at a refinery complex.[18] Natural gas processing plants often utilise chemical solvents to remove CO_2 from field gas in a process known as 'gas sweetening', which increases the calorific value of the gas to meet final product specifications. Physical solvents such as the Selexol™ and Rectisol® systems are currently in use in synthetic fuel manufacturing.

- Removal from oxy-fired streams: fossil fuels are combusted in an oxygen-rich environment, which leads to flue-gas with a relatively high concentration (80%>) of CO_2 and water vapour without nitrogen. After secondary treatment (particulate/contaminant removal), the CO_2 stream can be transported and stored. This option can be more energy efficient than the use of chemical solvents, however most conventional industrial process are not designed to operate in oxygen-rich environments and thus process adjustments are required. Oxy-firing industrial processes for the purpose of CO_2 capture are currently in the pilot phase in oil refining processes.
- Pre-process removal: this involves the gasification of fossil fuel or biomass in order to attain pure hydrogen or hydrogen-rich syngas which can be used as a product in further industrial processes or power generation. To increase hydrogen recovery, a product of the gasification process, carbon monoxide (CO), is converted to CO_2 via a water-gas shift reaction,[19] which is subsequently removed using absorption by solvents (see above "Removal from diluted streams" above), membrane separation or through the use of adsorption materials. Existing industrial processes which utilise pre-process CO_2 removal include hydrogen and ammonia production, coal/biomass to transport fuel conversion (CTL) and the direct reduced iron (DRI) process.[20]

For all the capture routes outlined above, new technologies are in development with the principle goal of increasing the efficiency of capture, and reducing capital and operating costs.

In certain industrial processes, the removal of CO_2 is an inherent part of the production stream, an unavoidable step to produce the desired product. For example, hydrogen production requires the removal of carbon monoxide and CO_2 from a hydrocarbon feedstock. This process results in a relatively concentrated stream of CO_2 of between 40% and 99%. The manufacturing of synthetic fuels,

[18] Although technically feasible, such applications may not be economically feasible
[19] A chemical reaction whereby carbon monoxide reacts with water vapour (steam) to form CO_2 and hydrogen in the presence of a metal-based catalyst
[20] DRI process involves the conversion of iron ore to iron through the use of a reduction gas, normally natural gas which is chemically converted to hydrogen and carbon monoxide

commonly through the gasification of coal and subsequent Fischer-Tropsch reaction, also requires the removal of CO_2. In these processes, a form of CO_2 capture from diluted gas streams is already deployed and the resultant CO_2 stream may only need to be compressed prior to transport and storage. The costs involved in deploying CCS in these industrial processes may be considerably lower than processes with no inherent CO_2 capture.

CO_2 transport options[21]

- Pipelines are the main option for large-scale CO_2 transportation, but shipping and road transport are also possibilities.

CO_2 storage options[22]

- Deep saline aquifers (saltwater-bearing rocks unsuitable for human consumption)
- Depleted oil and gas fields (with the potential for Enhanced Oil/Gas Recovery)
- Deep unmineable coal beds (with the potential to extract methane).

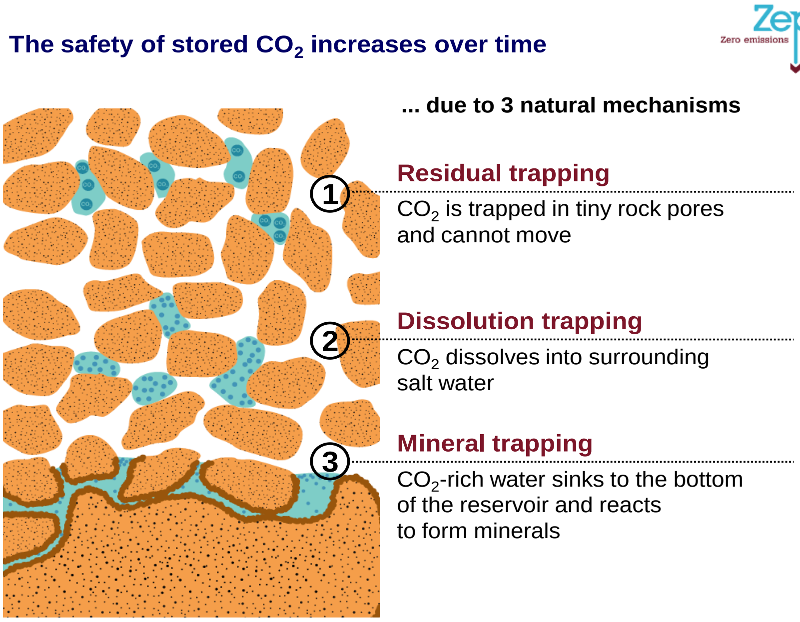

FIGURE 6 **CO_2 CAN BE STORED USING THE SAME NATURAL MECHANISMS THAT HAVE ALREADY KEPT HUGE VOLUMES OF OIL, GAS AND CO_2 UNDERGROUND FOR MILLIONS OF YEARS**

2.3 CCS technologies are already proven and being utilised globally

Although there are currently no fully integrated, commercial-scale CCS power projects in operation, many of the technologies that make up CCS have been in commercial use for decades:

- CO_2 capture is already practised on a small scale, based on technology that has been used in the chemical and refining industries for decades.
- Transportation is also well understood: CO_2 has been shipped regionally for over 20 years, while a 5,000 km pipeline network has been operating in the USA for over 30 years for Enhanced Oil Recovery (EOR).
- CO_2 storage projects have been operating successfully for over a decade, e.g. at Sleipner (Norway), Weyburn (Canada) and In Salah (Algeria). The industry can also build on knowledge obtained through the geological storage of natural gas, which has also been practised for decades.

[21] See ZEP, 2011. The costs of CO_2 transport. www.zeroemissionsplatform.eu/library.html
[22] See ZEP, 2011. The costs of CO_2 storage. www.zeroemissionsplatform.eu/library.html

2.4 Infrastructure planning for CCS can significantly reduce capital costs

Compared to Europe's large coal and lignite fired power plant sites with several generation units onsite, industrial production facilities are mostly characterised by rather small CO_2 emission levels. However, the co-location of multiple industries and power generation installations is a common occurrence in many European regions. Developing CO_2 capture solutions for energy-intensive industries in parallel to fossil-fuel power generation could facilitate the clustering of CCS projects, improving economies of scale for CO_2 transportation and storage, greatly reducing capital costs compared to stand-alone projects.

Specific CO_2 transport costs are determined by several factors, whereas the transport quantity (measured as mass flow) has a notable influence with disproportionally declining transport costs at increasing mass flow (Figure 7). Hence, considerable cost savings can be generated if CO_2 transport clusters are established for those capture sites that would have high transport costs for individual transport solutions, e.g. the cluster of 5 capture sources of 1 $MtCO_2$/yr each would lower the transport costs by ~60% and a further cluster to total 20 $MtCO_2$/yr would reduce transport costs by half.

With respect to today's location of fossil-fuelled power plants and industrial production sites, selected areas across Europe could be of potential interest for a joined effort to transport captured CO_2. For the neighbouring countries of the North Sea a central pipeline system connecting to large storage sites, such as the Utsira aquifer in the Norwegian North Sea, represents an infrastructure option which might be competitive to onshore storage in the long-run. The set-up and scale of clusters can range from joint efforts to bundle small-size emission sources, up to regional hubs as an integral part of a trans-European CO_2 pipeline infrastructure connecting multiple capture sites with large-scale CO_2 storage reservoirs.

Please also see ZEP's report, "Building a CO_2 transport infrastructure for Europe".[23]

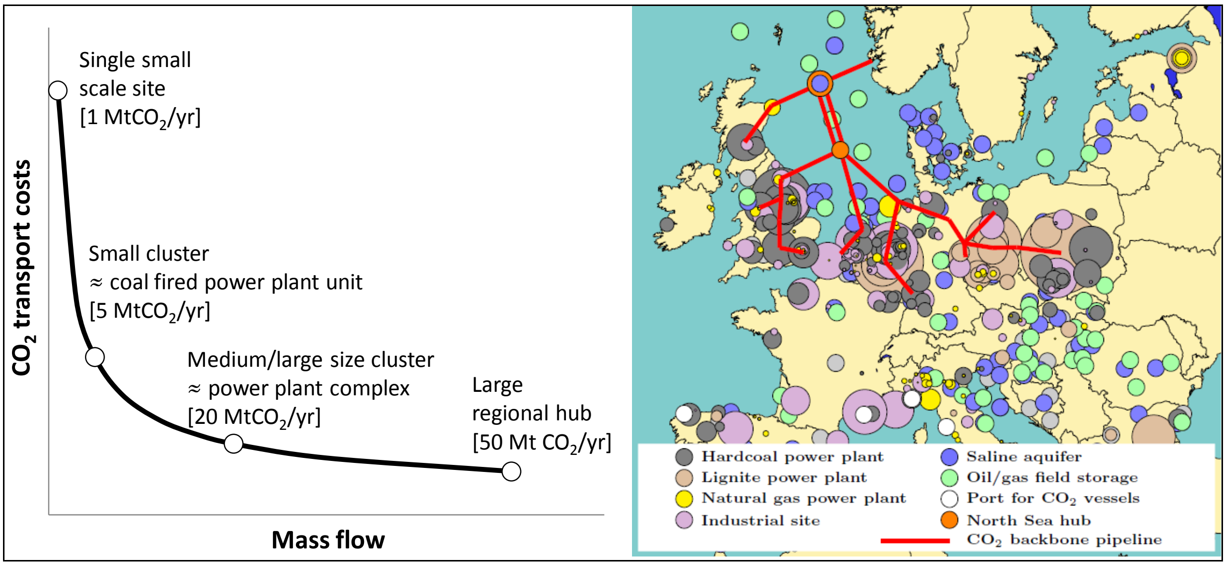

FIGURE 7 COST EFFECTS OF CO_2 TRANSPORT (LEFT) AND POTENTIAL CO_2 CAPTURE SOURCES AND STORAGE SITES, INCLUDING TRANS-EUROPEAN INFRASTRUCTURE FOR CO_2[24] [25] [26]

[23] www.zeroemissionsplatform.eu/library/publication/221-co-2transportinfra.html

[24] Blesl, M. and T. Kober. Bedeutung von CO2-Transport- und Speicheroptionen im europäischen Energiesystem, In Zeitschrift für Energiewirtschaft No. 34 (2010), p. 285-301 DOI 10.1007/s12398-010-0027-8

[25] Strachan, N., R. Hoefnagelsb, A. Ramírez, M. van den Broek, A. Fidje, K. Espegren, P. Seljom, M. Blesl, T. Kober, P. E. Grohnheit. CCS in the North Sea region: A comparison on the cost-effectiveness of storing CO_2 in the Utsira formation at regional and national scales, in the International Journal of Greenhouse Gas Control 5 (2011), p. 1517-1532

[26] van den Broek, M., A. Ramírez, H. Groenenberg, F. Neele, P. Viebahn, W. Turkenburg, A. Faaij. Feasibility of storing CO2 in the Utsira formation as part of a long term Dutch CCS strategy: an evaluation based on a GIS/MARKAL toolbox, in the International Journal of Greenhouse Gas Control 4 (2010), p. 351–366

3 Iron and steel production

3.1 The European steel industry

The EU accounts for ~15% of global steel production,[27] with nearly 180 million tonnes of crude steel produced within the EU27 in 2011.[28] The industry directly employs over 400,000 people, representing 1.25% of employment in EU manufacturing and achieves an annual turnover of ~€170 billion.[29] Although the energy efficiency of steel production has improved dramatically over the last 50 years, the production process of crude steel remains an energy-intensive process. CO_2 emissions from the EU 27 steel sector in 2010 was 182 Mt, representing ~5% of EU27 CO_2 emissions.

There are two leading processes for steel production in Europe. Primary steel production takes place at an integrated steel mill, where iron ore is converted into crude steel using coke, fluxes and other additives. This involves 1) raw materials preparation plants (i.e. coke, agglomerating, lime production units), 2) ironmaking 3) basic oxygen steelmaking and 4) continuous casting and finishing. In the EU, 60% of crude steel is produced in ~40 integrated steel plants. The second leading production route involves the processing of scrap or other scrap alternatives in an electric arc furnace (EAF) to produce crude steel. Recycling of scrap uses ~50% to 60% less energy compared to integrated steel production, however this route is limited by the availability of scrap supply and quality requirements. Europe currently has one of the highest scrap recovery rates globally – almost 85%.

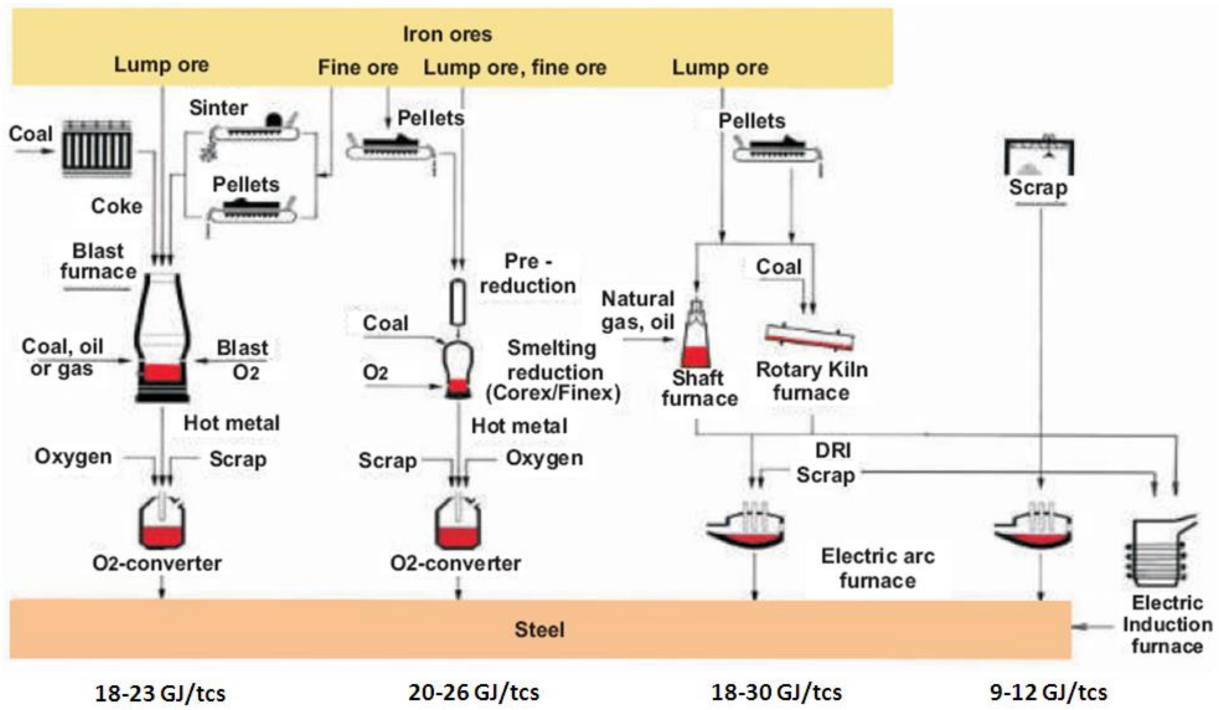

FIGURE 8 ENERGY INTENSITY AND SIMPLIFIED SCHEMATIC PFD OF DIFFERENT IRON AND STEEL PRODUCTION ROUTES

Sinter and coke production, ironmaking and steelmaking are responsible for 80% to 90% of the CO_2 emissions from the production of steel via the blast furnace to basic oxygen furnace (BF-BOF) route used

[27] Climate Action Network Europe, 2010. Steel, cement and paper – Identifying the breakthrough technologies that will lead to dramatic greenhouse gas reductions by 2050
[28] Eurofer, 2012. www.eurofer.org/index.php/eng/Facts-Figures/Figures/Crude-Steel-Production/All-Qualities
[29] Eurofer, 2012. Eurofer Press Statement

at integrated steel mills. However, it should be noted that the majority of the actual CO_2 emissions within the integrated steel mill occurs from users of the by-product fuel gases generated from the iron and steel production units. Between 70% and 80% of the CO_2 emitted per tonne of crude steel produced comes directly from the use of coal and coke as fuel and reductant for the blast furnace.[30] Generally, the ironmaking process (blast furnace) emits ~1.5 to 2.0 tCO_2/t of hot metal (thm - liquid iron) produced,[31] with the EU average ~1.65 tCO_2/thm. Modern blast furnaces deploying the best available technology and the use of higher grade raw materials are understood to be able to achieve CO_2 emissions of ~1.5 tCO_2/thm.[32]

3.2 Mitigation options for the steel industry

Many modern blast furnaces in Europe have been fully optimised to operate efficiently by minimising the use of fuel and reductants. Modern conventional blast furnaces in operation today therefore have a limited scope for further reductions of their CO_2 footprint.

Currently, several best practices have been incorporated in the operation of iron and steelmaking processes which should improve the energy intensity and CO_2 emissions per tonne of crude steel produced. Nonetheless, it should be noted that these best practices could only achieve CO_2 emissions reductions of 15% to 20% at most. These best practices include:

- Use of better grade raw materials input to the blast furnaces
- Higher level of scrap recycling at the BOF steelmaking process
- Increased utilisation of the different off-gases available on-site
- Various energy efficiency improvements and upgrades to the different iron and steelmaking processes, including the finishing mill.

Recognising the challenges associated with decarbonising the industry, the European steel community has led the Ultra-Low CO_2 Steelmaking (ULCOS Programme) since the year 2000. They have investigated a number of broad technological options which could offer potential pathways for CO_2 reduction in the ironmaking process. Three out of the four technologies selected for further development would require CCS to achieve at least 50% reduction of the CO_2 footprint per tonne of crude steel produced.

3.3 CO_2 capture options

CCS has been recognised by the steel community worldwide as the only option that could cut at least 50% of emissions from the global steel industry. The bullets below outline a number of innovative steel production routes in development, all of which can involve the use of CCS to maximise CO_2 abatement.

- **Modification to the operation of the conventional blast furnace**: the ULCOS blast furnace as shown in Figure 9 (also known as top gas recycling-blast furnace or TGR-BF) involves the removal of the CO_2 from the blast furnace top gas and the recycling of this top gas, primarily consisting of carbon monoxide (CO) and CO_2, into the blast furnace. The recycling of the top gas would consequently reduce the coke consumption that is needed to be fed into the blast furnace, resulting in a reduction of ~20% to 25% of the carbon input. Together with CCS, this should achieve a 45% to 55% reduction in the CO_2 footprint per tonne of crude steel produced.

  ULCOS has been developing the TGR-BF since early 2000. It was successfully tested and evaluated at LKAB's Experimental Blast Furnace at Lulea, Sweden between 2007 and 2008. The blast furnace is injected with nearly pure oxygen, rather than hot air, in order to reduce the nitrogen in the off gases, facilitating the separation of CO and CO_2. CO_2 is removed using physical adsorption techniques or PSA and then vented.

[30] IEAGHG, 2013. "Overview of the Current State and Development of CO2 Capture Technologies in Ironmaking Process", Report No. 2013-TR3
[31] IEA, 2009. Energy Balances of non-OECD countries, OECD/IEA
[32] Kerkoff, H.J. Stahlinstitut VDEh, November 2011

The ULCOS programme has led to two set of plans to demonstrate TGR-BF technology. This includes the planned conversion of blast furnaces to incorporate top gas recycling at Eisenhuettenstadt, Germany (to demonstrate version 3 of TGR-BF) and Florange, France (to demonstrate version 4 of TGR-BF). The planned demonstration at Florange was submitted for NER300 funding, but unfortunately failed to obtain it due to technical and commercial reasons; it is currently under review.

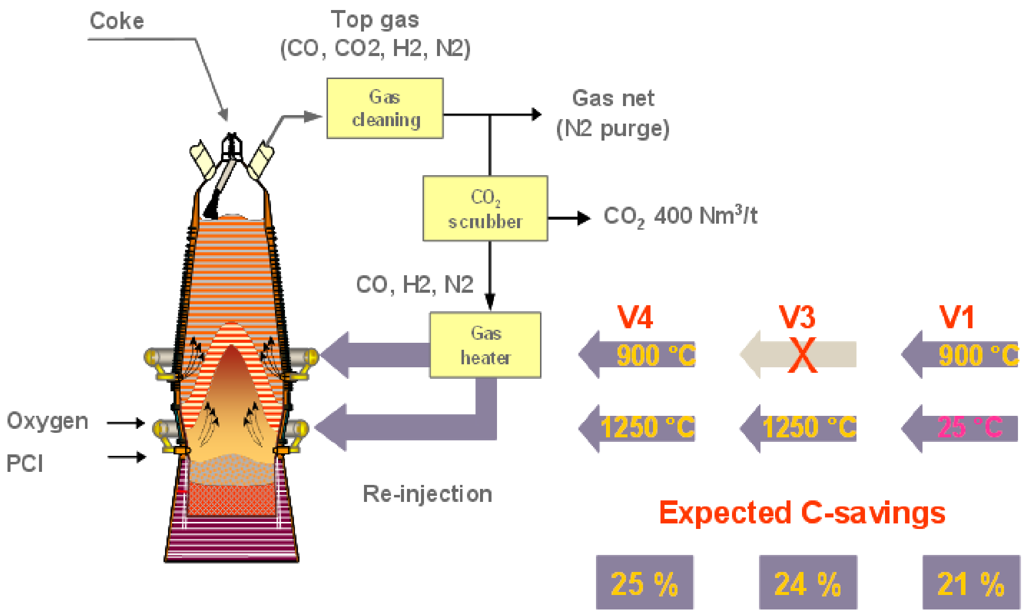

FIGURE 9 SIMPLIFIED SCHEMATIC FLOW DIAGRAM OF BLAST FURNACE WITH TOP GAS

- **Development of alternative hot metal production process**: under the ULCOS programme, an alternative hot metal production process has been developed. This involves a class of smelting reduction technology called HISARNA (see Figure 10). This is a combination of three different technologies: 1) heated screw coal pyrolysis feeder 2) cyclone converter furnace (CCF) and 3) HiSmelt vessel. This ironmaking process allows the direct use of fine ore and non-coking coal, therefore eliminating sinter (agglomerating) and coke production plants and reducing the number CO_2 emissions point sources within the site. HISARNA alone could reduce the CO_2 footprint of crude steel produced by 20%. Together with CCS, it could achieve a reduction of ~80% compared to the CO_2 footprint per tonne of crude steel produced from a conventional blast furnace. Furthermore, the use of biomass or other waste materials could replace part of the coal used in the operation of HISARNA.

  Currently, a pilot plant at Tata Steel's IJmuiden works produces 8 thm/d HM. This has recently completed its second experimental campaign phase and the indications are that objectives have been achieved, although these have not yet been publically reported. The third phase is scheduled for the spring/summer of 2013. It was assessed that the HISARNA technology, if demonstrated on a larger scale, could become commercially available after 2030. However, like any smelting technologies developed in the past decades, HISARNA would still face several technology development challenges.

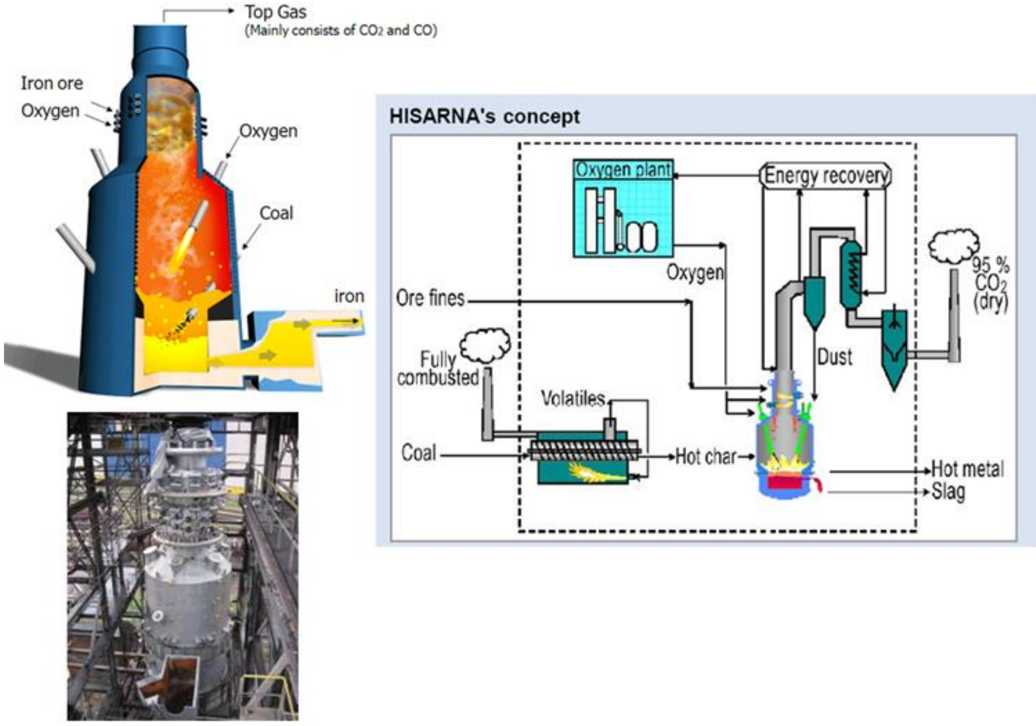

FIGURE 10 A SIMPLIFIED SCHEMATIC FLOW DIAGRAM OF THE HISARNA IRONMAKING PROCESS

- **DRI-based steelmaking:** sponge iron or Direct Reduced Iron (DRI) can be obtained through the direct reduction of iron ore using reducing gas in a shaft, fixed bed or fluidised bed reactors. The iron rich product (DRI) can be subsequently melted together with scrap in an EAF to produce crude steel. Provided that the natural gas is used as the main source of the reducing gas for the direct reduction process, and that the electricity used to melt the DRI in the EAF is derived from a source with a relatively low CO_2 intensity, the DRI process could lead to a significant reduction in the CO_2 footprint of 20% to 25% for every tonne of crude steel produced, compared to crude steel produced from the conventional BF-BOF route. The DRI process is currently not widely deployed in the EU,[33] due to high natural gas prices. However, this process – in combination with CCS – cannot be overlooked as an option for a CO_2-lean steel production process.

  ULCOS is currently developing "ULCORED", a shaft-based DRI production process using coal or gas as the source of their reducing gas. This is designed with CCS incorporated, which should lead to at least 50% reduction in the CO_2 footprint, compared to steel produced from the conventional BF-BOF route. The production of the DRI using gas-based ULCORED involves a shaft reactor fed with lump ore or pellets and uses nearly pure oxygen to burn pre-heated fuel in a partial oxidation reactor (POX) to produce the syngas as the primary reducing gas. The process involves the use of a shift reactor to convert at least 90% of the CO in the cleaned off-gas from the shaft reactor to produce H_2 and CO_2. The CO_2 is then separated using vacuum pressure swing adsorption (VPSA[34]) or pressure swing adsorption (PSA). There are currently plans to demonstrate this technology to produce 1t/d DRI at Lulea, Sweden.

- **CCS:** as mentioned above, in order to reduce direct emissions from the steel industry, CCS can potentially be applied to either a blast furnace equipped with TGR, or in combination with a new novel smelter design such as the HISARNA process. There are several technology options to separate CO_2

[33] Only one DRI plant is currently operating in Hamburg, Germany, producing 0.5 Mt of DRI in 2008
[34] VPSA is a non-cryogenic gas separation technology, a variant of PSA (see page 12)

from the top gases of TGR-BF or HISARNA. ULCOS currently favours the use of PSA/VPSA, or in combination with cryogenic separation. The final selection of the CO_2 separation technology is dependent on the CO_2 specifications for pipeline transport.

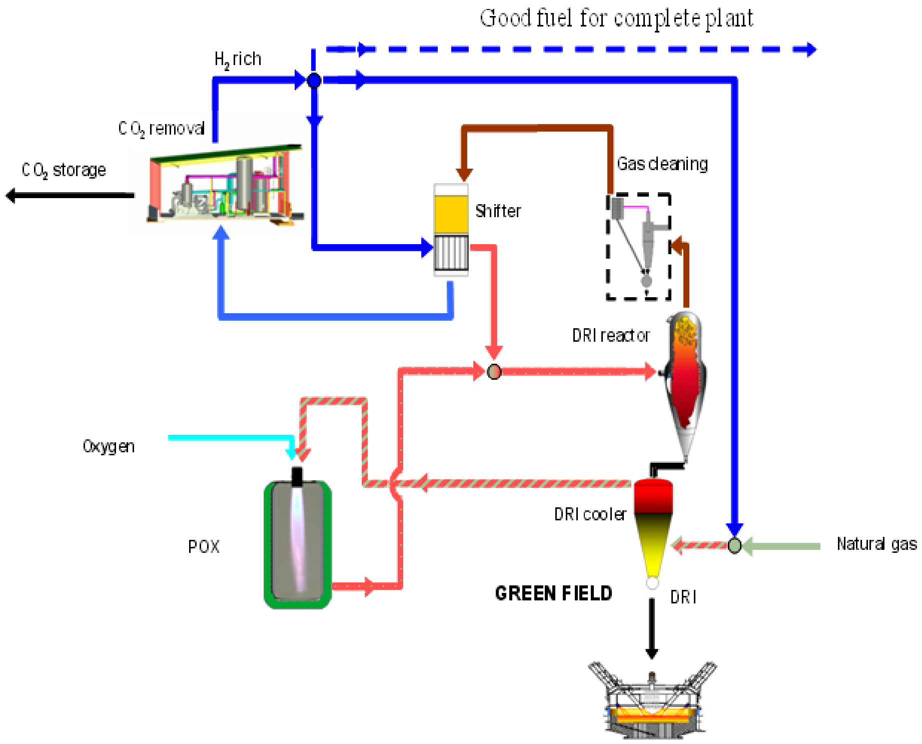

FIGURE 11 SIMPLIFIED PROCESS SCHEMATIC DIAGRAM OF GAS-BASED ULCORED PROCESS

3.4 Sector-specific challenges

Demonstration of TGR-BF in large-scale operation is necessary to validate the results obtained from LKAB's experimental blast furnace. Furthermore, the large -scale TGR-BF should be able to operate and demonstrate a full cycle of the BF operation (i.e. it should operate for at least 10 years in order to simulate a full campaign life of the blast furnace).

The experimental blast furnace campaign has successfully demonstrated the possibility of reducing the coke rate, but it must be validated in a larger-scale blast furnace. Key to this demonstration is the permeability and mechanical strength of the coke. There are also other challenges in the design and modification of a blast furnace – particularly the handling of the oxygen and the injection of the recycle top gas into the tuyeres and shaft which will require enhanced gas penetration and distribution. Further development in the design of the heating equipment of the recycled top gas is also necessary. This involves the handling of high CO and H_2 gas at temperatures greater than 900°C.

The different components of HISARNA have been demonstrated separately in various pilot and industrial facilities. For example, the cyclone converter furnace was successfully demonstrated at IJmuiden steelworks in the 1990s. A large-scale Hismelt producing 0.6 Mt per year of hot metal has also been demonstrated at Kwinana, Australia.

Current experience at the HISARNA pilot shows that integration of the different technologies would require several fine tuning and adjustments. In particular, the reliability of the oxygen lances, coal injection equipment and cooling staves, as well as the durability of the refractory, must be proven. Similar to the

TGR-BF, a scaling up of the current HISARNA pilot plant by 5 times of its current capacity (i.e. from the production of 0.06 to 0.3 million tonnes per year of hot metal) is necessary to fully validate the performance observed at pilot-scale level.

All major components of the gas-based DRI reactor are in commercial operation (shaft reactor, shift reactor, PSA/VPSA and POX). However, integrating these components to produce the DRI and capture the CO_2 at the same time would require large-scale demonstration to test availability, reliability and the quality of its products (DRI and CO_2). Development of the pilot plant is an important element in the demonstration of ULCORED. This should provide the opportunity to establish and validate the different technical and economic parameters in the integration of the various components of ULCORED.

4 Cement production

4.1 The European cement industry

Cement production in the EU, which closely follows trends in the construction sector, has been negatively affected by the economic crisis. In 2007, total cement production in the 27 Member States reached a peak of 270 Mt. In 2010, this had dropped to 190 Mt, ~6% of global production.[35] Regardless of the challenging economic conditions, four of the five largest cement producers Lafarge (France), HeidelbergCement (Germany), Holcim (Switzerland) and Italcementi (Italy), are based in Europe. In the EU, there are ~270 cement production plants and the sector employs 45.000 people directly.

In 2010, CO_2 emissions from the cement industry in the EU totalled ~100 $MtCO_2$. Cement production is an energy-intensive process and generates substantial CO_2 emissions. The most energy-intensive component in the production of cement is generally referred to as clinker burning. This process involves gradually heating calcium carbonate ($CaCO_3$) with small amounts of additives in a kiln. At ~900ºC, calcination occurs and CO_2 is released from the calcium carbonate.

As the reaction reaches its peak temperature of ~1450ºC, clinkerisation starts, whereby the calcium oxide reacts and agglomerates with silica, alumina and ferrous oxide, forming the primary component of cement – clinker. The clinker is then ground with other minerals to produce cement. Calcination accounts for ~60% of the direct CO_2 emissions associated with cement production, with the remaining emissions stemming from fossil fuel combustion to provide the process heat.

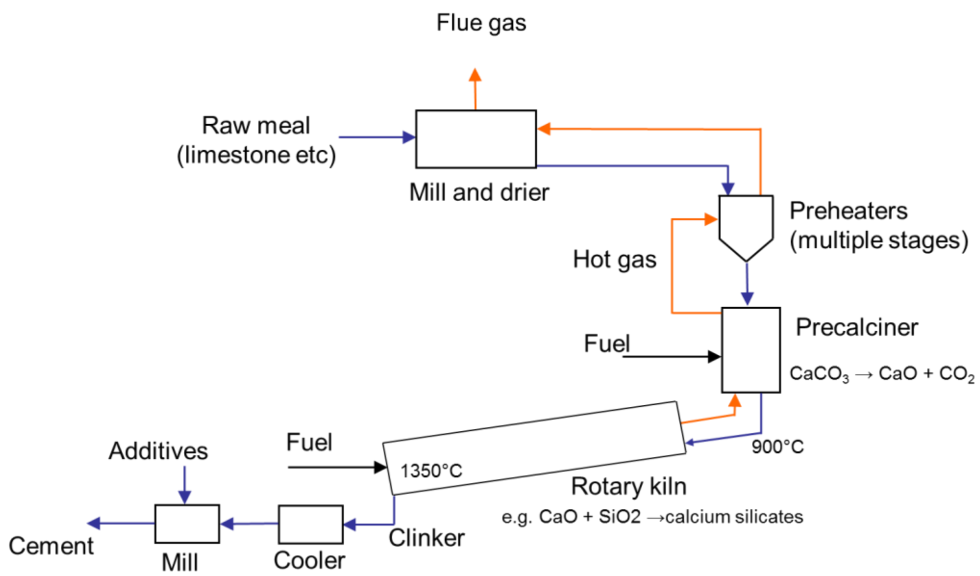

FIGURE 12 SIMPLE PROCESS FLOW DIAGRAM OF CEMENT PRODUCTION

In the EU, ~80% of cement plants have CO_2 intensities of 0.80 to 1 tCO_2/t clinker,[36] influenced by the type of plant and fuel for combustion. The average performance of the 10% most-efficient installations in the EU cement sector is understood to be 0.77 tCO_2/t clinker.[37]

[35] www.cembureau.eu/sites/default/files/AR2011.pdf
[36] Ecofys, 2009: Methodology for the free allocation of emission allowances in the EU ETS post 2012 – Sector report for the cement industry
[37] European Commission, 2011: Commission Decision 2011/278/EU

4.2 Mitigation options for the cement industry

CO_2 emissions from the calcination process to produce the clinker are inherently unavoidable. Beyond the implementation of best available techniques (BAT), there are no breakthrough technologies foreseen for the improvement of thermal energy efficiency in the cement sector. The average heat consumption of the EU industry was 3.6 GJ/t clinker in 2006 and it is understood that 3.2 GJ/t on a yearly basis is an engineering limit.[38]

- **Combustion of waste and biomass fuels in the kiln**: conventional fuels in cement kilns are petcoke and coal, however alternative fuels include municipal waste and biomass. A cement plant in Brevik, Norway, utilises on average 25% biomass-based kiln fuel, achieving a carbon intensity of 0.76 tCO_2/t clinker.[39] The use of alternative fuels has significant CO_2 reduction potential, however there are availability issues with certain wastes and biomass.
- **Increased use of clinker substitutes in cement blending**: clinker can be blended with by-products such as fly ash from coal combustion or slags from the steel industry. Blended cements can be mixed with up to 65% slags or 35% fly ash,[37] which of course reduces the CO_2 intensity of the final product. However, this option is limited by the local availability of such substitutes and blended cements with a large non-clinker component are generally considered less favourable for building purposes.
- **CCS**: CCS can reduce emissions both from the calcination process and fuel combustion. The point sources at a cement plant with relatively high concentrations of CO_2 (14% to 33%) mean that post-combustion capture could be applied to the plant without disrupting the core process.

4.3 CO_2 capture options

CCS is the only means of reducing emissions from the production process by up to 80%, given that energy efficiency improvements, fuel and clinker substitutions have in many cases been exhausted.

Post-combustion capture of CO_2 from the cement industry using solvents involves similar capture technologies to those in the power sector (e.g. amine scrubbing). Such technologies are currently regarded as the most commercially mature, with the advantage that they can be retrofitted to existing plants at low technical risk. It has been estimated that 80% of CO_2 emissions from a cement plant could be abated using post-combustion capture. In 2013, Gassnova, the Norwegian state enterprise for CCS, was given the authority to grant ~€10 million in state aid to the Norwegian cement firm Norcem, to test post-combustion CCS at the existing Brevik cement plant in Norway.[40] The test centre, which will first operate on a 'catch and release' basis, will operate for between three to five years, with a focus on minimising energy demand and observing the degradation rate capture solvents.[41]

The use of oxy-fuel technology in the cement production process is an alternative production process that may provide a more cost-efficient CO_2 capture mechanism. In this process, the pre-calciner and kiln are heated by combusting the fuel in a controlled oxygen/CO_2 atmosphere. This avoids flue gas being diluted with nitrogen present in conventional combustion with air, resulting in a high concentration of CO_2 that may be purified by less energy-intensive techniques than amine scrubbing, such as VPSA. Despite initial research suggesting that, due to numerous process design changes, the deployment of oxy-fuel capture would be restricted to new-build cement plants, recent work by the European Cement Research Academy (ECRA) indicates that retrofitting the technology is feasible. Initial concerns regarding kiln modifications due to oxy-fuel conditions and air ingress diluting the CO_2 stream appear manageable. Laboratory testing of the clinker produced in small-scale oxy-fuel pilots has also indicated negligible physical property differences compared to conventional production routes.[41]

[38] SETIS, 2010. DRAFT Report of the SET-Plan workshop on technology innovations for energy efficiency and greenhouse gas (GHG) emissions reduction in the cement industry in the EU27 up to 2030
[39] http://hcne-sustainability.nu/sites/default/files/NO_Brevik_LOW_June2012.pdf
[40] EFTA Surveillance Authority, 2013. State Aid – State Aid: Green light given for Norwegian CCS project in the cement industry. Press release PR13(12)
[41] ECRA, 2012. ECRA CCS Project – Report on Phase III. Technical report, TR-ECRA-119/2012. European Cement Research Academy, Dusseldorf

A specific CO_2 capture route that could be utilised in the cement industry is carbonate looping. The low pressure flue gas of a conventional cement kiln is passed through a vessel whereby the CO_2 is adsorbed by calcium oxide (CaO) in a process known as carbonation, producing calcium carbonate ($CaCO_3$). The remaining (primarily CO_2-free) gas is then released. Next, the calcium carbonate is passed to a calciner, where CO_2 is released from the CaO sorbent which can then be recycled to the carbonation phase. This is a technology mainly developed in Europe, involving major CFBC technology manufacturers due to the mechanical and thermal similarities with this type of power plant. This has facilitated a rapid scale-up in recent years from a paper concept to MW-scale pilots – in both the FP7 CaOling project[42] and other European and national projects.[43 44]

Carbonate looping is understood to be capable of reducing the CO_2 content of the exhaust gases of cement kilns by 80%. The major benefits of carbonate looping are the potential energy savings and reduced operating costs compared to other post-combustion capture routes such as amine scrubbing. Although this technology is at an early stage of development, preliminary investigations have estimated CO_2 avoidance costs lower than conventional post-combustion CO_2 capture systems, with minimum process efficiency losses of between 5% and 8%.[45] It is currently being assessed by the cement industry as a potential retrofit option for existing kilns and in the development of new oxy-firing kilns.

4.4 Sector-specific challenges

Although CCS for the cement industry appears to be moving forward both in research and demonstration, a number of technical challenges remain. Reducing the energy demand for solvent regeneration in post-combustion systems must be prioritised, as cement plants have few residual heat sources that can be (partly) used for this purpose.

Cement plants are primarily located close to limestone quarries and are therefore unlikely to be close to potential sources of heat from other installations. In most cases, an additional installation such as a combined heat and power (CHP) plant will be required to provide low pressure steam and electrical power for the CO_2 capture and compressor plant.

An accelerated degradation of amine-based solvents can be caused through high-levels of sulphur dioxide (SO_2), oxygen and iron particles entering the absorber and it is recommended that CCS-ready cement plants must keep SO_2 limits below 10ppm.[41] This may require integration of enhanced SO_2 removal units and corrosion-free steel in some plants. The planned cement CCS plant in Brevik, Norway, is likely to contribute to the remaining technical issues regarding post-combustion capture in the industry.

Small-scale pilots conducted by ECRA indicate that basic refractory materials used to build cement kilns are able to withstand oxy-fuel conditions. The small amount of laboratory clinkers produced under oxy-fuel conditions were also tested for compressive strength, showing ‘negligible’ differences compared to standard clinker. Air ingress, which could dilute the CO_2 concentration, can be minimised by improved maintenance and reducing gaps on kiln inlets, outlets, feed ports and inspection doors.

Nevertheless, the use of oxy-fuel technology in the cement industry remains at pilot scale and changes to the pre-calciner and clinker cooler require further investigation. A large-scale plant is needed to demonstrate that switching to oxy-fuel production will not be to the detriment of the end product. The optimal CO_2 processing unit may develop in line with oxy-fuel demonstration in the power sector, particularly with regard to achieving a suitable CO_2 purity for transport and storage. It is expected that the deployment of oxy-fuel cement installations will require different air separation technology that uses between 20% and 30% less energy than conventional systems.

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[42] Sanchez-Biezma et al 2012, GHGT11. Testing post combustion CO_2 capture with CaO in a 1.7 MW pilot facility.
[43] Plötz, S., et al., 2012. First carbonate looping experiments with a 1 MWth test facility consisting of two interconnected CFBs. Proceedings of the 21st International conference on fluidized bed combustion, Naples 2012.
[44] Dieter, H., et al. 2012. The 200 kWth dual fluidized bed calcium looping pilot plant for efficient CO2 capture: plant operating experiences and results. Proceeding of the 21st International conference on fluidized bed combustion, Naples, 2012.
[45] Epple, B., 2007. Fluidised bed based CO_2 capture by carbonate looping

5 Refining

5.1 Emissions from the European refineries

The EU has ~100 mainstream refineries, with an emissions profile that varies widely due to facility size, products produced, feed quality and complexity. The number of operating oil refineries in the EU has been in decline since 2008 with several site closures. This is due to many factors, including high crude price, low refinery margin, weaker domestic demand, capacity under-utilisation, surplus gasoline production and competition from developing and petroleum exporting countries. Half of the refineries operating in the EU emit less than 1.3 Mt of CO_2 annually, roughly equivalent to a medium-scale, gas-fired power generation plant. However, there are also eight larger facilities that produce over 3 Mt of CO_2 per year, with the largest emitting ~5.5 Mt CO_2. In 2010, the refinery sector accounted for ~15% of the EU's direct industrial emissions.

Oil refineries are responsible for processing crude oil in order to produce more valuable petroleum products such as liquid petroleum gas (LPG), naphtha, gasoline, kerosene, diesel, gas oil and fuel oil. Crude oil is typically heated to ~300°C to 400°C in a crude distillation column using fired heaters. In this column, as the vapour rises it cools and condenses into liquids which are then separated (depending on their differing boiling points), forming the basis for the light petroleum products mentioned above. Heavier components of the distillation process will undergo further processing in a fluid catalytic cracker (FCC) and platformer to produce more gasoline and other light products, or in hydrocrackers to produce more diesel and heavy fuel oil.

Refineries are complex industrial sites that are highly integrated and characterised by diverse process configurations. Thus, a single site will have numerous possible CO_2 emissions points. Generally speaking, a complex refinery emits between 0.2 and 0.4 tonne CO_2 per tonne of crude processed for simple to medium conversion refineries; and can reach between 0.7 and 0.8 tonne CO_2 per tonne of crude processed if delayed cokers or residue gasifiers are installed.

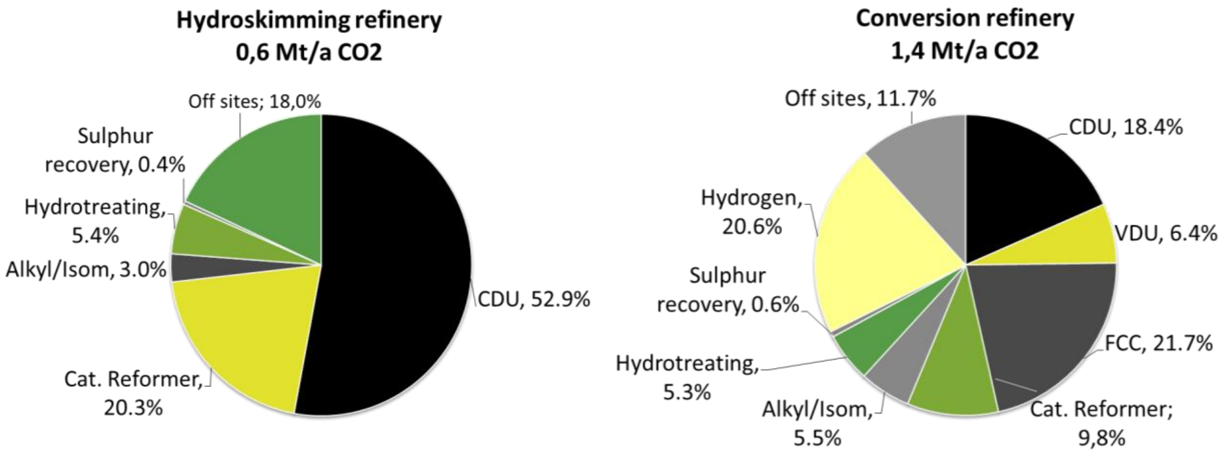

FIGURE 13 CO_2 EMISSION SOURCES FROM A HYDROSKIMMING AND MORE COMPLEX CONVERSION REFINERY[46]

Figure 13 shows a breakdown of CO_2 emissions by process from a hydroskimming[47] refinery and a more complex conversion[48] refinery. In the EU, medium to high conversion refineries are more prevalent, with

[46] Concawe, 2011. The potential for application of CO_2 capture and storage in EU oil refineries. Report 7/11.
[47] Hydroskimming refineries are a relatively simple type of refinery, equipped with a crude distillation unit (CDU), catalytic reformer and hydro-treater. Hydroskimming refineries can produce gasoline, diesel and jetfuel, however up to 40% of the output is gas oil and heavy fuel oil that are considered relatively low-value products.
[48] A conversion refinery is able to maximise the amount of higher value fuels produced to ~90% to 95%, involving a vacuum

75% of refineries equipped with vacuum distillation units (VDU) and fluidised catalytic crackers (FCC) in addition to crude distillation units (CDU).[49]

5.2 Mitigation options for refineries

The CO_2 emission intensity of a refinery is influenced by the energy efficiency of various processes, the type of fuel used,[50] the feed composition of the crude oil[51] and the desired products.[52] With reference to these variables, a number of broad options for reducing CO_2 emissions in the refinery sector are possible and some of these are briefly described below:

- **Energy efficiency**: based on evidence from a pre-existing literature review,[53] individual site-level analyses have estimated that heat integration and waste heat recovery measures can achieve energy savings of between 6% and 30%. Process integration and optimisation, monitoring and maintenance of heaters and boilers, and the installation of high-efficiency motors for pumps can also improve efficiency. Typical energy savings from total site analysis indicate potential energy savings of between 20% and 30% and are highly site-specific.[54]
- **Fuel shift**: typically, a major part of the fuel used in a refinery consists of refinery off-gases, fuel oil and natural gas. Refinery off-gases are by-products of refining processes, consisting of light hydrocarbons which served as the primary fuel. Fuel demand is then balanced by fuel oil (low-value liquid fuel) which is relatively CO_2-intensive. Any further fuel deficit is met by purchased natural gas. Replacing fuel oil with natural gas could reduce CO_2 emissions by up to 15%.[49] However, this type of shift would result in a lower refinery margin and require major investment to process the lower-value fuel oil.
- **CCS**: the scope for energy efficiency gains that would lead to deeper CO_2 emissions reductions in highly optimised European refineries is quite limited. The energy consumption of European refineries is also likely to increase due to new International Maritime Organisation regulation limiting the use of high sulphur heavy fuel oil in ships towards 2020.[55] This will require further processing at refineries. CCS is emerging as a key mitigation route for the refining sector as no other feasible alternative exists, or is likely to be developed, that can substantially reduce CO_2 emissions.

5.3 CO_2 capture options

There are four major emission routes at refineries which are potentially compatible with CO_2 capture technologies. These include process derived CO_2 emissions resulting from hydrogen production and the fluid catalytic cracker (FCC); and from combustion derived emissions from fired process heaters, and utilities for on-site power and steam generation.

Combustion derived emissions produce the majority of CO_2 at refineries; however, the CO_2 is generally at low pressure and concentrations (4% to 15%, similar to power plants). These are often situated at various locations depending on where the flue gas stacks are located. Process derived emissions may have a higher CO_2 concentration depending on the process technology and thus could have a lower cost of capture.

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distillation unit (VDO) and a fluidised catalytic cracker

[49] Johansson, D. (2013). System studies of different CO_2 mitigation options in the oil refining industry: Post combustion CO2 capture and biomass gasification. Chalmers University of Technology, Sweden.

[50] Refinery fuels include purchased natural gas and (by)products of various refinery processes, such as produced fuel gas and liquid fuels (distillate and residual fuel oil) and coke. Process heaters utilising produced fuel gas will have fewer emissions than those using residual fuel oil.

[51] Light (lower density) and sweet (lower sulphur content) crude oils require less energy to process

[52] Higher quality, low sulphur-containing transport fuels require enhanced processing which consumes more energy

[53] Johansson, D., Franck, P.A. Berntsson, T., 2013. CO_2 capture in oil refineries: Assessment of the capture avoidance costs associated with different heat supply options in a future energy market. Energy Conversion and Management. 66, p. 127-142.

[54] Brown SM, 1999. The drive for refinery energy efficiency. Petroleum Technology Quarterly, p. 45-55.

[55] www.imo.org/ourwork/environment/pollutionprevention/airpollution/pages/sulphur-oxides-(sox)-%E2%80%93-regulation-14.aspx

Process	Description	% of total refinery emissions	CO_2 concentration in stream
Hydrogen production	Requirement for many processes. Growing demand and contribution to CO_2 emissions	5-20%	95-99% (chemical absorption) 40-70% (PSA)
Fluid catalytic cracking	Crude oil refining	20-50%	10-20%
Process heaters	Heat and steam production	30-60%	8-10%
Utilities	Electricity/steam use at refinery	20-50%	3-12%

TABLE 1 POTENTIAL PROCESSES SUITABLE FOR CCS IN REFINERIES[56]

It is therefore expected that there will be no single 'CO_2 capture' solution that will be applicable across the industry or to all facilities. Instead, it will require a suite of different technology solutions with differing costs of capture and varying time of deployment. This should result in various possibilities for CO_2 capture solutions requiring varying process optimisation requirement. Such solutions are dependent on the processes present at a particular oil refinery site and could vary from facility to facility.

In European oil refineries, CO_2 capture solutions would require retrofit options rather than new build. In this respect, the diverse nature of the refining process should be not perceived as disadvantageous as this offers the possibility of modular CO_2 capture deployment.

- **Hydrogen production**: 5% and 20% of CO_2 emissions from a refinery are linked to the production of hydrogen (H_2), whereby CO_2 removal is an inherent part of the process. Increasing demand for higher grade fuels has led to increase demand for hydrogen upgrading of common fuels. This has required new dedicated systems be deployed at refineries, the most common being steam methane reforming (SMR). SMR produces a mixed syngas of H_2, CO and CO_2, which is then subject to a water-gas shift reaction to leave a mixture of H_2 and CO_2. The CO_2 needs to be removed to produce an adequately pure stream of hydrogen. Depending on the CO_2 removal process, the resulting CO_2 stream concentration can be between 40% and 99%.
- **Fluid catalytic cracking (FCC)**: in some cases, this process can contribute up to 50% of refinery emissions and is often the single largest source of CO_2. Depending on the process selection and quality of feedstock, the CO_2 concentration in the flue gas can range from 10% to 20%.[57] The emissions from FCCs are process related rather than combustion related, and associated with the regeneration of a catalyst used in the process. As the concentration of CO_2 in the flue gas is similar to that of a coal-fired power plant, the use of post-combustion technology, such as amine or chilled ammonia CO_2 capture, could be a viable option for CO_2 capture. These technologies are currently demonstrated at Mongstad Refinery in Norway. However, new emerging technologies such as oxyfiring of the FCC is also currently being evaluated at a pilot plant in Brazil and considered an option.
- **Utilities**: refineries require a large amount of steam and electricity to meet the energy demand of the different processes. Steam is provided on-site and in order to increase efficiency, may be undertaken in conjunction with electricity production via cogeneration of heat and power. In some cases, natural gas is used as fuel for the industrial gas turbines producing electricity, while waste heat is recovered and utilised to produce steam. As these processes closely mirror those used in the power sector, this implies that opportunities for applying CO_2 capture in the utility installations of the refineries will follow the development of CO_2 capture technology in the power sector.
- **Process heaters**: refineries employ numerous fired heaters and boilers of different sizes and capacity throughout the facility. These could have capacities ranging between 2 MW and 250MW, and a typical

[56] Based on Concawe, 2011. The potential for application of CO_2 capture and storage in EU oil refineries. Report 7/11.
[57] De Mello, L., Pimenta, R., Moure, G., Pravia, O., Gearhart, L., Milios, P., & Melien, T., November 2008. A technical and economical evaluation of CO2 capture from FCC units. Paper presented at Green House Gas Technologies 9, Washington DC, USA, p.16-20.

refinery could have between 20 and 30 different interconnected processes around the site. This heating equipment usually uses different types of fuel that are available on-site, thus producing flue gas with a wide-ranging CO_2 composition. Together, these dispersed emission sources could contribute the largest share of refinery CO_2 emissions and, in some cases, could contribute up to 60% of the total emissions. However, it should be noted that it is not unusual for some of these emission sources to be connected to a single stack.[58] Combined stacks can have CO_2 concentrations as high as 15%, emitting up to 1.2 Mt/CO_2 per year. [59]

5.4 Sector-specific challenges

The application of CCS in refineries is challenging due to the fact that CO_2 is emitted from many sources, which may be dispersed and could be relatively small compared to other industrial sectors. On-site hydrogen production could provide relatively low-cost opportunity for CO_2 capture at refineries and even though this process accounts for ~5% to 20% of total plant emissions, at larger sites the total CO_2 available can reach 1 Mt per year.[59]

However, not all hydrogen production routes at a refinery are equally suitable for CO_2 capture. Two separation processes dominate: chemical absorption (primarily using MDEA), or pressure swing adsorption (PSA). The use of MDEA can lead to a very pure stream of CO_2 (up to 99%), which could be directly compressed, ready for transport and storage. PSA however, produces an off-gas with a CO_2 concentration of ~40% to 70%, together with CO, methane (CH_4) and some hydrogen. This off-gas is generally used as supplementary fuel for the furnace of the reformer. Despite this, it is technically possible to retrofit a hydrogen production unit utilising PSA with either pre- or post-combustion CO_2 capture.[60]

Beyond the possibility of capture from hydrogen production, process heaters collectively represent the largest CO_2 sources.[58] The technical feasibility of CO_2 capture from process heaters is highly dependent on plant configuration, and the availability and accessibility of combined stacks. To maximise the CO_2 captured from various sources, the possibility of ducting multiple flue gas streams to a single CO_2 capture unit has been investigated.[61] Retrofitting process heaters with CO_2 capture equipment and installing ductwork is likely to be challenging due to the large additional footprint that would be required at existing sites. As with many applications of post-combustion capture, the low concentration of CO_2 in the process heater flue gases mean that significant additional heat would be required for solvent regeneration.

In the longer term, the utilisation of specific oxy-fuel combustion technologies for refineries offers the potential to reduce the energy penalty of CO_2 capture. Pilot-scale testing under the Carbon Capture Project (CCP) has confirmed the technical viability of retrofitting a FCC to enable CO_2 capture via oxy-firing. Through oxy-firing, the CO_2 concentration in the flue gas of the FCC was increased to between 93% and 95%, from a base case of 15% during conventional operation. Capturing emissions from a FCC can reduce total refinery emissions by 20% to 30%. However, these promising results will need to be validated by scaling up to larger test facilities with greater feed flow rates.[62]

The CCP has also conducted pilot-scale testing using conventional process heaters for oxy-fired operation.[63] This was proven to work with minor modifications, particularly for flue gas recycling to control the combustion temperature. Finally, oxy-fuel combustion technology at pilot scale was evaluated by John Zink at the CCP for natural draft-fired heaters, where fired heaters were converted to oxyfiring with recycling of the flue gas.

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[58] IEA, 2012. CCUS AG Working Group on CCS in Industrial Applications – Background Paper

[59] Straelen, J. van, F. Geuzebroek, N. Goodchild, G. Protopapas, L. Mahony., 2009. CO_2 capture for refineries, a practical approach. Energy Procedia 1, p. 179-185

[60] Ferguson, S., & Stockle, M. 2012. Carbon capture options for refiners. An outline methodology identifies the most appropriate way to achieve a refinery's carbon capture goal. Foster Wheeler Engineering.

[61] Simmonds, M., Hurst, P., Wilkinson, M.B., Watt, C., Roberts, C.A., 2004. A study of very large scale post combustion CO_2 capture at a refining and petrochemicals complex. Proceedings of 6th Conference Green House Gas Control Technologies.

[62] The pilot-scale test involved a feed-flow rate of 33 barrels of hydrocarbon feed per day (equal to 1 tCO_2/d), with large industrial FCC units able to process over 75,000 barrels per day

[63] Carbon Capture Project, 2013. Annual report 2012.

6 The chemical industry

6.1 The European chemical industry

The chemical industry covers a broad array of processes, mainly involving the conversion of fossil-fuel feedstocks (e.g. natural gas, naphtha and ethane) into a range of intermediate industrial materials, fertilisers and consumer chemicals. In highly integrated chains, the industry produces petrochemicals (ethylene, propylene), basic inorganics (ammonia, chlorine) and polymers (polyethylene, polypropylene), which serve as the 'building blocks' for industries producing end products such as plastics, rubbers and fertilisers. Only 30% of the combined output of the chemical industry is sold to end users. In the EU, the chemical industry accounts for ~1.1% of GDP and directly employs ~1.2 million people.[64]

In 2010, the chemical industry accounted for 15% of total direct CO_2 emissions in the EU, emitting 141 $MtCO_2$. Around 70% of these emissions relate to the combustion of fossil fuels for heat generation, with the remainder related to process emissions. This chapter will focus on two of the main processes within the chemical industry: steam cracking and ammonia production.

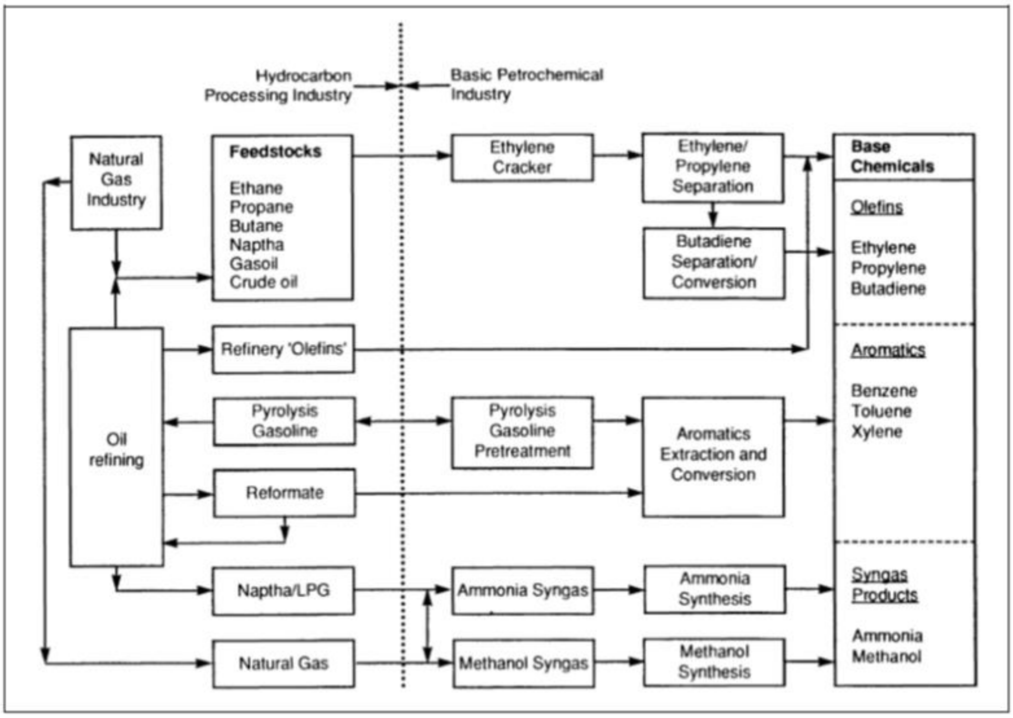

FIGURE 14 THE BASIC PETROCHEMICAL INDUSTRY AND INTERFACE WITH HYDROCARBON PROCESSING[65]

The most fundamental process in the petrochemical industry is the 'steam cracking' of saturated hydrocarbons such as naphtha, butane and ethane into olefins such as ethylene and propylene. Super-heated steam at ~800°C is used to drive the process and the heat requirement of the steam cracking process accounts for the majority of combustion related CO_2 emissions from the chemical industry. The predominant feedstock in the EU is naphtha, which has an approximate CO_2 intensity of between 0.7 and

[64] CEFIC, 2013. European chemistry for growth – Unlocking a competitive, low carbon and energy efficient future. CEFIC, Brussels
[65] EC DGXI, 1993. Techno-economic study on the reduction methods, based on BAT of industrial emissions (air, water and wastes) from the basic petrochemical industry. WRc plc.

1.3 tCO_2/t ethylene,[66] with the lower figure representing a cracker utilising best available techniques (BAT).[67] There are ~50 steam crackers operating in the EU, with an average capacity of 0.6 Mt/y.[68]

Ammonia is one of the most commonly used inorganic chemicals in the world, with 80% used for the production of fertiliser. In Europe, the primary route for ammonia production is based on steam methane reforming (SMR), whereby hydrogen produced from natural gas is combined with nitrogen that has been separated from air. The steam-reforming of natural gas also results in a significant amount of CO_2, all of which has to be removed as part of production process. In the EU, there are 55 ammonia plants in operation, with an average capacity of 0.7 Mt/y.[68] The majority have a CO_2 intensity of 1.5 to 2.0 tCO_2/t NH_3, with the lower figure based on a specific energy consumption of 29 GJ/t NH_3.

6.2 Mitigation options for the chemical industry

Given the broad spectrum of processes used within the chemical industry, the possibilities for CO_2 mitigation are equally as diverse. The European Chemical Industry Council (CEFIC) has categorised the primary mitigation options for the entire sector, which are summarised below.[69]

- **Feedstock evolution**: the use of bio-based feedstocks has significant potential and is already implemented in some countries. Chemically identical bio-based building blocks such as bio-ethylene and bio-methanol can be used to produce a wide range of products currently manufactured by fossil-fuel feedstocks. High-value feedstocks could be achieved through the gasification of post-consumer plastics, which would replace the use of virgin feedstocks and close the carbon cycle to some extent.
- **Energy efficiency**: there remain significant incremental efficiency improvements in the recovery and reuse of heat, and the efficient use of power – particularly in motor systems. For example, experts predict that the approximate energy demand of new ammonia plants can be reduced from 28 GJ/t NH_3 in 2020 to 26 GJ/t NH_3 in 2050, moving towards the theoretical minimum of 23 GJ/t NH_3. For cracker units, potential improvements in energy efficiency are considerable, with energy demand potentially being reduced to 9 GJ/t[70] by 2050, compared to the current EU average of 18 GJ/t cracker products.[64]
- **Heat source changes:** depending on geographical location, some chemical processes could use geothermal heat sources, or solar heat applications. The use of CHP is already widespread, but this could be combined with biomass to reduce CO_2 emissions even further.
- **CCS**: for the larger CO_2 sources in the chemical industry, such as ammonia production and steam cracking, CCS is a potential mitigation option. CO_2 sources from other chemical processes, such as methanol and ethylene oxide production, could also be considered for CCS, but may prove less favourable due to smaller CO_2 volumes.

6.3 CO_2 capture options

CO_2 removal is an integral part of ammonia production. Typically achieved by chemical absorption, this can result in an off-gas with a near-pure stream of CO_2 which, in most cases, is vented to the atmosphere. If 99% of the process related CO_2 emissions were captured and stored, total CO_2 emissions from ammonia production could be reduced by 65% to 70%. Combustion emissions from steam production used in ammonia production are not conducive to CO_2 capture unless the associated boiler is large enough and supplies heat to multiple installations.[71]

There are examples of the use of near-pure process emissions from ammonia production: the Enid Fertiliser plant in Oklahoma, USA, has been capturing ~0.6MtCO_2/yr since 2003, using the CO_2 for EOR. In

[66] European ethylene producers committee, EEPC issue group
[67] European Commission, 2003. Reference document on best available techniques in the large volume organic chemical industry
[68] Ecofys, 2009. Methodology for the free allocation of emission allowances in the EU ETS post 2012 – Sector report for the chemical industry.
[69] The technical feasibility of and mitigation potential of such options are highly process specific, so no specific figures are provided here. For a full evaluation, please see CEFIC, 2013. European chemistry for growth – Unlocking a competitive, low carbon and energy efficient future.
[70] The figure equates to an approximate CO_2 intensity of 0.55 tCO_2/tonne cracker product

2009, Dutch chemical company DSM also announced a project to capture CO_2 from an existing ammonia production facility and store it in coal seams at a depth of 1,800 metres. This appears to have been cancelled due to local and national opposition to onshore CO_2 storage. In line with ongoing and planned projects, the IEA has highlighted CCS projects involving ammonia plants as low-cost opportunities for an initial portfolio of CCS projects by 2020.[71]

Compared to industrial processes in other sectors, there has been little research into the applicability of CCS for ethylene production. The CO_2 concentration in the flue gas is estimated to be ~13% to 15% and with only one flue, it may be possible to capture up to 90% of emissions from a cracker – around 75% to 88% of total emissions avoided.[71] Due to the necessity of additional heat for regeneration for the capture solvent, an additional heat source would be required on-site.

6.4 Sector-specific challenges

Ammonia production is often integrated to produce one of the two basic types of nitrogen fertiliser, urea. Here the CO_2 captured during ammonia synthesis is utilised to produce urea and therefore CCS would not be possible as the majority of CO_2 is temporarily stored in the urea before being released during agricultural use. Production of the other basic type of nitrogen fertiliser, ammonia nitrate, does not involve CO_2, which is all released at the ammonia plant. Although urea is the dominant nitrogen-based fertiliser globally, it accounts for ~20% of demand in Europe, where ammonia nitrates are the prevalent fertiliser.[72] This indicates that a greater number of ammonia production plants in Europe would have near-pure steams of CO_2 available for storage.

The introduction of pressure swing adsorption (PSA) as an energy-efficient alternative to conventional chemical or physical CO_2 absorption processes during hydrogen production may reduce the immediate feasibility of CCS at ammonia production plants. In such cases, the resultant gas stream following PSA may have a CO_2 concentration of only 30% to 40%, meaning that it would have to undergo further treatment prior to transport and storage.[73] [74] In some cases, the waste gas stream containing a lean mixture of H_2 and CO_2 is used as a low-calorific fuel on-site, which means that the use of CCS would be more disruptive to plant operations.

The volume of CO_2 available from an ammonia production plant can also affect the feasibility of CCS deployment. Based on an average plant capacity in the EU of ~0.7Mt/y NH_3, this equates to ~0.5 to 0.8 $MtCO_2$/yr available for storage, depending on plant efficiency and feedstock.[75] Commercial CCS projects must take advantage of economies of scale, which means that smaller ammonia plants may be less suitable for stand-alone CCS projects due to increased investment requirements in transport and storage infrastructure.

Ammonia production plants, due to the integral CO_2 capture during the process, are recognised as a potential low-cost opportunity for CCS projects. There are existing and planned CCS projects involving ammonia production in the U.S., Canada and Australia. However, in order to fully assess the potential for CCS in the EU, the prevalence of integrated ammonia/urea plants and PSA CO_2 capture within European installations must be substantiated. The feasibility of CO_2 capture on steam crackers faces similar challenges to most post-combustion applications, particularly the requirement for heat to regenerate the chemical solvent. The highly integrated nature of chemical production complexes could also pose problems in terms of siting a CO_2 capture and compression plant.

[71] IEA, 2009. Technology Roadmap – Carbon capture and storage. IEA/OECD.
[72] Yara, 2012. Yara fertilizer industry handbook – February 2012
[73] Carbon Counts, 2010. CCS Roadmap for Industry: High-purity CO_2 sources – Sectoral assessment.
[74] Of course, this is no reason to avoid introducing more energy-efficient technologies such as PSA in the chemical sector
[75] Based on a 70% capture rate and 75% capacity utilisation.

7 CCS in industrial sectors and EU climate policy

7.1 CCS: an indispensable route to an EU low-carbon economy

In 2011, the Commission released a Communication entitled, "A roadmap for moving to a competitive low carbon economy in 2050"[76] Which detailed a modelling exercise used to explore pathways for reducing GHG emissions by 80% compared to 1990 levels. In order to reach this goal, the model outcomes highlight that emission reductions will be required in *all* sectors, with CO_2 emissions from the industrial sectors reduced by 34% to 40% by 2030 and by 83% to 87% by 2050. The Commission has deduced that in order to achieve these reductions most cost-effectively,[77] CCS will need to be widely deployed in energy-intensive industries from 2035.

7.2 EU climate policy provides little incentive to invest in low-carbon technology

Until 1st January 2013, non-energy related GHG emitters included in the EU Emissions Trading Scheme (ETS) were insulated from any additional operating costs associated with emission unit allowance (EUA) prices. With the commencement of the third ETS trading period from the start of 2013, certain manufacturing industries will no longer be freely allocated sufficient EUAs to cover all emissions. Nevertheless, with the lack of a global climate agreement, the Commission also recognises the threat of loss of EU competiveness and potential carbon leakage associated with increasing the domestic production cost of globally traded products.[78]

For industrial sectors deemed at risk of carbon leakage, which account for ~90% of EU GHG emissions from non-power ETS installations, such installations are entitled to a free allocation of EUAs based on historic activity levels.[79] The Commission has introduced the use of product-specific benchmarks based on the average of the top 10% most-CO_2 lean sector installations, which could theoretically leave some CO_2-intensive installations short of EUAs. Nevertheless, the use of pre-crisis historic activity levels in allocation calculations and the current drop in productivity, along with EUA prices far below any previous projections, mean that the EU ETS will not provide a sufficient incentive for CCS in industry in the short to medium term.

7.3 The carbon leakage dilemma

Although reports that attempt to estimate the threat of carbon leakage to certain industrial sectors are numerous and often conflicting, the possibility of carbon leakage occurring, given excessive carbon constraints on EU industry, cannot be denied. However, although the approach of free allocation may be highly effective in subduing competiveness issues, achieving the levels of abatement outlined in the 2050 roadmap *without* laying the foundations for the broad deployment of CCS today will become increasingly difficult and costly. The continued exclusion of such a large proportion of CO_2 emitters from the EU ETS also undermines the effectiveness of the market-based system, which aims to deliver emissions reductions at the lowest cost. There are a number of CO_2 capture options within industrial sectors with significant abatement potential that can be achieved at lower costs than in the power sector.[80]

7.4 A 2015 global agreement does not ensure a level playing field for EU industry

It is broadly agreed that a global agreement on CO_2 emissions reductions is the only pathway to prevent carbon leakage. Assuming that such an agreement under the UNFCCC is established by 2015, with subsequent implementation of agreed policy actions by 2020, it is a risk to assume that the principle of

[76] EC, 2011a. A roadmap for moving to a low carbon economy in 2050. COM(2011) 112 final.
[77] With a delayed deployment of CCS, other low-carbon technologies and energy efficiency measures needed to compensate for this will require an EUA price of €370/tCO_2 compared to a balanced technology deployment scenario carbon price of €190/tCO_2 by 2050 (source: Impact assessment – A Roadmap for moving to a low carbon economy in 2050).
[78] EC, 2010. Analysis of options to move beyond 20% greenhouse gas emission reductions and assessing the risk of carbon leakage. COM(2010) 265 final.
[79] Baselines using the mean production between 2005-2008, or 2009-2010 if output was higher
[80] Brown, T., Gambhir, A., Florin, N. and Fennell, P. 2012. Reducing CO_2 emissions from heavy industry: a review of technologies and considerations for policy makers. Briefing paper No 7, Grantham Institute for Climate Change, Imperial College London.

‘common but differentiated responsibilities’ established in the 1992 Rio Declaration and which informs the UNFCCC, will be abandoned. An unequal abatement burden and corresponding economic pressures are likely to continue for a number of decades and companies in certain sectors will therefore continue to have a motivation to relocate investment and production to regions with less ambitious CO_2 targets. Actions and policies are therefore needed which support EU industrial competitiveness in preparation for continued asymmetric global climate commitments.

Leakage and loss of competitiveness

Leakage occurs when GHG abatement policies implemented in one jurisdiction cause an increase in GHG emissions in foreign jurisdictions. There are two main types of leakage relevant to industrial sectors:

1) Through the relocation of economic activity (i.e. industrial production) from implementing jurisdictions to foreign jurisdictions with an absence of or less stringent monetary constraints on emissions
2) Through a shift in investments in new plants or plant expansions in the same direction.

These two types of leakage are likely to occur simultaneously and can severely undermine the effectiveness of regional GHG abatement policies in contributing to a reduction in global GHG emissions. **Competitiveness loss** can be caused by the regional implementation of GHG policies, which represent an additional charge on the final product which cannot be passed through to intermediate/manufacturers or consumers of globally traded products. As a consequence, the implementing jurisdiction would experience a loss of profits, market share and related jobs.

8 Actions to support CCS in energy-intensive industries

8.1 Enable investment in demonstration towards 2020

This report has documented several possibilities for integrating CO_2 capture technologies into a number of existing and emerging industrial processes. However, for the majority of these processes, CO_2 capture remains at either R&D or small-scale pilot phase. Significant investment is therefore needed in the near-term in order to substantiate performance and reliability, and develop operational and safety standards in line with existing industrial practices.

Many of the remaining technical challenges outlined in this document can only be overcome by large-scale testing. Near-term actions, both at national and European level, must therefore focus on supporting the technological progress of industrial CCS applications by enabling the shift from small-scale pilots to large-scale demonstration projects.

In principle, the second call of the 'NER300'[81] could provide partial funding for the demonstration of CCS in energy-intensive industries; however, the current design of the scheme is not ideally suited to industrial applications. The current modality of the scheme focuses on achieving the maximum amount of CO_2 stored for the lowest amount of funding requested. The production of CO_2 is of course related to the production rate, which can be uncertain given an excess of production capacity in many industrial sectors in Europe, the current recession and international competition. It may be more appropriate to reward targets for the lowest possible CO_2 intensity of industrial product achieved via the utilisation of CCS.

8.2 Long-term ETS reform is necessary to facilitate post-2020 commercialisation

If the EU ETS is to remain the key instrument for reducing CO_2 emissions from fossil fuel combustion to 2050, a structural reform of the EU ETS will be necessary to move towards more sustainable investment conditions which allow the transition between demonstration and commercialisation. Although cost estimations for CCS from energy-intensive industries are currently uncertain and highly variable, any investment in the technology will require an EUA price of at least €40 for the lower end of the cost curve, excluding transport and storage. The Commission has estimated an oversupply of ~2.3 billion EUAs up to 2012,[82] and this could reach 2.5 billion with the maximum use of international credits.[83] [84] This amounts to ~15% of the amount of EUAs to be auctioned between 2013 and 2020.

An increased EUA price can be achieved by reducing the number of EUAs allocated in Phase III between 2014 and 2020, either temporarily or permanently. The Commission has identified a number of options for reducing the over-supply of credits to the market: increasing the EU's GHG reduction target with consequential increase of the annual reduction factor (currently 1.74%); retiring a number of Phase III EUAs permanently; bringing more sectors into the EU ETS; limiting access to international credits; or a discretionary price management mechanism such as a price management reserve.

According to market observers, the current proposal for a temporary set-aside of 900 million EUAs for the years of 2013-2015, later to be auctioned in 2019 and 2020, may raise EUA prices to between €10 and €20 up until 2015. However, a surplus is still expected into the mid-2020s without additional measures or aggressive economic growth.[85]

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[81] In 2008, the EU agreed to set aside 300 million EUAs from the New Entrant Reserve (NER) under the EU ETS Directive to demonstrate CCS and innovative renewable energy technologies. The first call did not lead to the establishment of any CCS demonstration projects primarily due to economic constraints.

[82] European Commission, July 2012. Commission Staff Working Document, COM(2012) 416 final

[83] External credits refer to Certified Emission Reductions (CERs) and Emission Reduction Units (ERUs) generated respectively by the Kyoto Protocol flexible instruments, the Clean Development Mechanism and Joint Implementation Mechanism

[84] Verdonk, M. & Vollebergh, H., 2012. Evaluation of the European Commission's proposal to set aside emission allowances – Effects on the EU carbon price and Dutch ETS companies.

[85] European Commission, 2012. Commission Staff Working Document – Proportionate Impact Assessment

8.3 Further EUA set-aside auctioning can raise funds for CCS development in industry

Recently, the Center for Clean Air Policy (CCAP) outlined a comprehensive proposal to structurally reform the EU ETS and link the changes to an enhanced European industrial policy.[86] The primary action is the withdrawal – commonly termed a 'set-aside' – of 1.4 billion EUAs,[87] which are supposed to be auctioned in the period 2013-2020. These EUAs would be gradually set aside in parts of 200 million annually between 2015 and 2021.

In parallel, EUA scarcity can be achieved through an increase in the annual reduction factor from 1.74% to 2.5% and limiting the use of international credits.[88] Of the 1.4 billion EUAs set-aside, 900 million could be placed in a new Industrial Low-Carbon Transformation Fund designed to support the breakthrough of low-carbon technologies, while preserving EU industrial competiveness (see text box below). The remaining 500 million set-aside would form a Quantitative Easing Reserve, which would be used ensure price stability to help de-risk investment.

CCAP Europe: an Industrial Low-Carbon Transition Fund

Based on an average EUA price of €20, auctioned in parts of 100 million EUAs annually between 2015 and 2023, CCAP estimates that the 900 million EUAs set-aside for the Industrial Low-Carbon Transition Fund may generate up to €18 billion. CCAP proposes a number of activities and policies to use the fund to effectively support CCS and other breakthrough technologies:

- **An EU Advanced Research Project Agency – Industrial** (€2 billion): to support high potential, high impact technologies which are too early for private investment.
- **Industrial CCS feed-in tariff** (€2 billion): feed-in support of €30/tonne of CO_2 stored in addition to an EUA price of €20 could enable the storage of 60-70 Mt of CO_2, equivalent to two to three industrial projects over 10 years.
- **European Investment Fund capitalisation** (5 billion): this fund would be used to de-risk and leverage finance for industrial low-carbon transition.

8.4 The 2013 EU CCS Communication and other ongoing EU policy processes

The case for addressing the threat of climate change becomes ever stronger, with warnings from the scientific community growing louder and signs of warming becoming clearer – notably in the Polar regions.[89] With the ongoing economic malaise in the EU, and the resulting drop in industrial activity discussed in section 1.5, it is clear that ways must be found to combine large-scale decarbonisation with ensuring employment and securing an industrial base in Europe.

In March 2013, the Commission launched a consultative CCS Communication[90] in order to gain input from relevant stakeholders on how CCS can be moved forward in Europe given the economic situation and not least in light of the EUA price, which currently fails to provide any notable price signal for low-carbon investments. The Communication was launched together with a consultative Green Paper[91] for the post-

[86] CCAP, 2013. The New Deal – An enlightened industrial policy for the EU through structural EU ETS Reform. The Center for Clean Air Policy-Europe.
[87] Equivalent to $1.4GtCO_2$
[88] If, for political reasons, the use of international credits are favoured, this should be compensated by a further increase of the reduction factor
[89] Average Monthly Arctic Sea Ice Extent. US National Snow and Ice Data Center (NSIDC), June 2013. http://nsidc.org/arcticseaicenews/files/2013/06/Figure3.png
[90] European Commission, March 2013. The Future of Carbon Capture and Storage in Europe. http://ec.europa.eu/energy/coal/ccs_en.htm
[91] European Commission, March 2013. A 2030 framework for climate and energy policies. http://ec.europa.eu/energy/green_paper_2030_en.htm

2020 EU climate and energy framework and ZEP underlines the necessity of viewing both consultations in a holistic way.

The Commission's CCS Communication reaffirms the critical role of CCS in meeting the EU's energy, climate and societal goals. It also recognises that CO_2 capture in several industries is significantly easier than in the power sector due to the relatively higher flue gas concentrations of CO_2, highlighting the steel sector as an example: "the potential application of CCS to the industry could result in a dramatic reduction of direct emissions". At the same time, the Commission recognises that strong economic and regulatory support is needed if EU industries competing in a global market are to deploy CCS.

This was echoed by Jos Delbeke, the Commission's Director-General for Climate Action, in a speech[92] at the 2013 European Steel Day following the sector's presentation of its work on a low-carbon 2050 roadmap for EU steel production. Mr. Delbeke declared that the Commission is *"preparing the ground for using part of the ETS related revenues to support energy-intensive industries in the quest to develop innovative low-carbon technologies...I see a lot of merit in focusing specifically on supporting the final stages of the innovation cycle, that is to say large-scale demonstration and deployment."* The sector itself also acknowledged[93] that "a functioning infrastructure for CCS" in the EU is a prerequisite to achieving large-scale decarbonisation.

The Commission's follow-up EU "Steel Action Plan" went even further, specifically naming CCS as a key decarbonisation technology for the sector and underlining the need for an "industrial scale demonstration project of producing steel with CCS". The Action Plan also highlights the necessity for financial support measures in order to proceed to demonstration and deployment via "for instance a new NER 300 call, a further European Energy programme for Recovery, or the use of structural funds."[94]

EU Energy Commissioner, Günther Oettinger, has already called for a re-industrialisation strategy to complement existing EU energy and climate strategies (July 2012).[95] The Commissioner for Enterprise and Industry, Antonio Tajani, has also presented a Communication on industrial competitiveness,[96] with a commitment to reverse the decline of industry in Europe, aiming to boost its weight from ~16% of GDP today to 20% by 2020 (October 2012). With this symbolic target – in line with the '20-20-20 goals' for climate and energy[97] – the Communication clearly underlines the importance of industry to the EU economy, employment and the welfare of its citizens.

It is therefore no surprise that the European Parliament's Environment Committee (ENVI), in its latest vote on the so-called "backloading" of EUAs in the EU ETS (19th June 2013), attempted to strike a balance between reducing emissions and securing a strong EU industrial base, after its original Report had been rejected by the Parliament Plenary (16th April 2013).[98] The ENVI vote underlined the need to avoid industry relocation outside of the EU as a result of climate-related regulation. At the same time, ENVI called for two-thirds of the EUAs that the Commission has proposed[99] to remove from the carbon market (and freeze for later auctioning) to be "made available to set up a fund to support the development of innovative low-carbon technologies, demonstration projects and measures intended to reduce the costs and carbon emissions of energy-intensive industries", as well as for "social and skill-related aspects of the low-carbon transition".[100]

This call seems to echo the signals from the Commission to the EU steel sector, which could be assumed to apply equally to other energy-intensive EU industries that face similar challenges, both in terms of global

[92] European Steel Day, 16th May 2013. http://ec.europa.eu/clima/news/articles/news_2013051602_en.htm
[93] www.eurofer.be/index.php/eng/News-Media/Press-Releases/EUROFER-shift-to-low-carbon-economy-creating-enormous-tensions
[94] http://ec.europa.eu/enterprise/sectors/metals-minerals/files/steel-action-plan_en.pdf
[95] Der Spiegel. www.spiegel.de/wirtschaft/unternehmen/oettinger-will-industrie-wie-klima-schuetzen-a-844556.html
[96] European Commission, October 2012. A Stronger European Industry for Growth and Economic Recovery. http://ec.europa.eu/enterprise/policies/industrial-competitiveness/industrial-policy/communication-2012/index_en.htm
[97] 20% of EU end-use energy from renewable sources, 20% energy efficiency and 20% GHG reduction by 2020
[98] http://www.europarl.europa.eu/oeil/popups/summary.do?id=1260015&t=e&l=en
[99] http://ec.europa.eu/clima/news/articles/news_2012111203_en.htm
[100] http://www.europarl.europa.eu/news/en/pressroom/content/20130617IPR12344/html/Environment-Committee-reaffirms-support-for-emissions-trading-fix

competition and ever stricter emissions reduction requirements. In order to reconcile these ambitions, the current strong relationship between economic growth and increased CO_2 emissions must be decoupled. As recognised in the Commission's CCS Communication, the application of CCS to industrial processes would enable the EU to enjoy future industrial growth while still achieving its long-term climate objective.

8.5 Longer-term actions are dependent on a global agreement

There are several ways in which competitiveness and leakage concerns may manifest post-2020. Firstly, there may be no global agreement on the appropriate relative sharing of burdens in addressing climate change. In this case, it seems likely that EU action may put it at the forefront of countries taking strong unilateral actions – a position it occupies today. Secondly, there may be global accord on the relative burden sharing that assigns hard targets to all countries, but such an accord might well assign heavier responsibilities for action to the EU than to other countries, meaning a differential in the costs imposed on some EU industrial sectors vis-à-vis their foreign competitors.

The latter case would represent an accord on 'acceptable leakage' – an agreement that while some leakage could occur, there were still hard mitigation targets in all countries. In this case, the legitimate policy options available to the EU would be limited to trying to lower the costs of compliance for EU industry, e.g. through support to R&D. But in the case of a world dominated by uncoordinated unilateral action, the EU might legitimately seek to limit the amount of leakage that does occur, such that the mitigation sought under EU climate regulations actually occurs at a global level.

8.6 Options for preventing climate leakage

Border carbon adjustment measures
One possible tool for achieving this sort of environmental effectiveness is border carbon adjustment (BCA), or imposing charges or demands at the border that will compensate for the different costs imposed on domestic vs. foreign producers.

While this sort of mechanism is intuitively simple, the details of how it could function are anything but: it involves a difficult navigation among the often competing objectives of environmental effectiveness, administrative feasibility and compliance with international legal obligations, even before political considerations are factored in. The International Institute for Sustainable Development has developed guidance on potential tools that could be implemented, taking into consideration trade and investment law obligations, the need for environmental effectiveness and administrative feasibility.[101]

The first characteristic of such a scheme is that it should focus on preventing leakage only – not on preserving competitiveness or achieving negotiating leverage. It should also be used only as an adjunct to price-based regulations such as cap and trade, or a carbon tax. Exemptions from coverage should be granted in any of the following circumstances:

- To countries that are party to a multilateral climate agreement to which the EU is also a Party
- To countries that have imposed an effective national cap on their domestic emissions, or to sectors covered by an effective sectoral cap
- To LDC producers, if a way can be found to make this trade legal.

There should also be calibrated credit granted to foreign regimes that undertake price-based actions to mitigate GHG emissions. Non-price-based foreign regulations would receive no credit, the necessary translation being too difficult and too prone to system gaming. Any exemptions or special treatment applied at national level would need to be accompanied by strong provisions to avoid trans-shipment, or shipment of 'dirty' goods through exempted countries to avoid adjustment. BCA should be accompanied by a host of

[101] Cosbey, A., Droege, S., Fischer, C., Reinaud, J., Stephenson, J., Weisher, L and Wooders, P. A guide for the concerned: Guidance on the elaboration and implementation of border carbon adjustment. Policy report 03, November 2012. www.iisd.org/publications/pub.aspx?pno=1716

good governance institutional features, including the ability to appeal any judgments, timely notice to exporters, clear and transparent criteria for adjustment that are regularly reviewed and clear sunset provisions.

It is recommended that adjustment be applied to imports, not exports: firstly, because it is impossible to avoid trans-shipment to countries that should not benefit from exemptions; secondly, because adjustment applied only to imports captures most of the potential for leakage; and finally, because export adjustment has uncertain trade law status. Ultimately, BCA as a policy option is necessarily imperfect and only to be contemplated in the event of failure to reach climate cooperation at a multilateral level. However, within the space provided by those caveats, it is useful to know that there are ways to elaborate and implement BCA that would represent best possible practice.

International sector approaches
International sector agreements could potentially minimise the risk of carbon leakage occurring within certain sectors, e.g. by setting emission performance targets for key industrial processes taking place in multiple countries. The implementation of sector agreements may broaden the participation of countries reducing CO_2 emissions in industrial sectors and could be an alternative option to BCA, or operate alongside it as a constructive mechanism to gradually reduce the necessity for border adjustments. The scope of sectoral approaches is broad and their precise design dependent on the prevailing climate agreement and overall goal of the system.

There are examples of international industrial initiatives. For example, the Cement Sustainability Initiative (CSI) set up by the World Business Council for Sustainable Development (WBCSD) involves 24 major cement producers in 100 different countries, in both developed and developing nations. A strong advocate of the sectoral approach to CO_2 mitigation, the CSI recognises that although a global agreement is the ultimate goal, large-scale emissions abatement activities can already start at regional or national level. Efforts have been focused on developing a consistent monitoring, reporting and verification (MRV) system, a global database of CO_2 and energy use, and the development of a global technology roadmap for possible abatement options.[102]

The majority of industrial companies in many energy-intensive sectors operate globally, which strongly facilitates technology transfer. Industrial initiatives such as the CSI could provide a basis on which governments can engage with industry and initiate policy to strengthen CO_2 abatement targets – potentially to a level whereby CCS becomes an economically feasible technology.

[102] World Business Council for Sustainable Development – Cement Sustainability Inititative, 2013. Sectoral market mechanisms. www.wbcsdcement.org/index.php/key-issues/climate-protection/sectoral-market-mechanisms#1

Annex I: Members of the ZEP Working Group 'CCS in Other Industries'

Name	Organisation
Carlos Abanades	Spanish National Research Council
Bruce Adderley	Tata Steel
Antti Arasto	VTT
Philip Beer	Linde Group
Simon Bennett	IEA
Per Brevik	Norcem
Michiel Carbo	ECN
Aaron Cosbey	International Institute for Sustainable Development
Eleni Despotou	IMA-Europe
Paul Fennell	Imperial College London
Bravo Ferreira	Secil Cement Group
William Garcia	CEFIC
Reinier Gerrits	VNCI
Claude Heller	Air Liquide
Jonas Helseth, *Chairman WG*	Bellona Europa
Jacques Kiewiet	Air Liquide
Daan Jansen	ECN/University of Utrecht
Kristin Jordal	SINTEF
Tom Kober	ECN
Ulrich Koss	Alstom Power
Wilfried Maas	Shell
Rob Van der Meer	Heidelberg Cement
Tom Mikunda, *Lead Author*	ECN
Benedicte Prodhomme	Alstom Power
Andrea Ramirez	University of Utrecht
Henk Reimink	World Steel Association
Stanley Santos, *Lead Author*	IEA GHG
Hermione St. Leger	St. Leger Communications
Jørild Svalestuen	Gassnova
Sebastian Teir	Cleen
Tore Torp	Statoil (retired June 2013)
Chris Treadgold	Tata Steel
Sven Unterberger	EnBW Kraftwerke
David Valenti	Eurofer
Keith Whiriskey	The Bellona Foundation

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